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Magnetotail: Unsolved Fundamental Problem of Magnetospheric Physics

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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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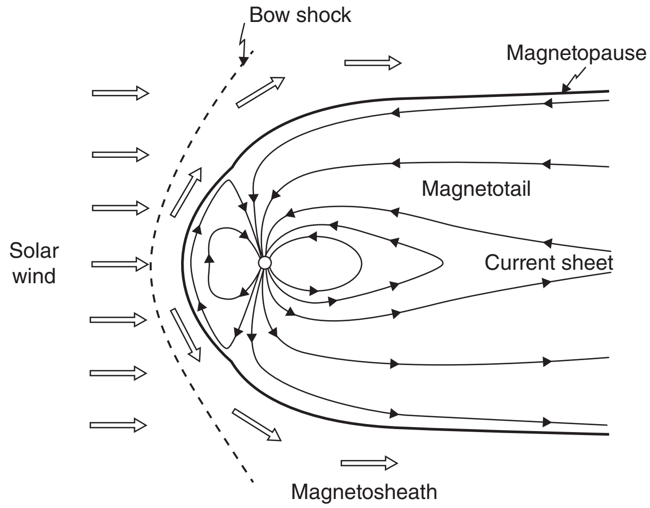

Figure 1.1 Schematic view of a magnetosphere, cut in the noon-midnight meridian plane. Open arrows: solar wind bulk flow. Solid lines within magnetosphere: magnetic field lines. The figure continues to the right out to distances in general much larger than the width of the figure. (In all figures of 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):

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

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,

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

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

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

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

$$\mathbf{T}_G = -\mathbf{gg}/4\pi G + \mathbf{I}\left(g^2/8\pi G\right) \qquad (1.4)$$

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

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

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,

$$\mathbf{F} = \int d\mathbf{A} \cdot \left[\mathbf{BB}/4\pi - \mathrm{I}\left(B^2/8\pi\right) - \mathrm{P} - \rho\mathbf{VV}\right], \qquad (1.6)$$

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

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

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

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

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

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

the rate of change can be written as

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

[*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

$$\mathrm{F} \simeq M\left(d^2\mathbf{R}/dt^2 - \mathbf{g}_{\mathrm{ext}}\right) \qquad (1.11)$$

where gravity has now been taken into account, with $\mathbf{g}_{\mathrm{ext}}$ 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

$$\mathbf{F}_{\mathrm{Pl+MS}} \simeq \left(M_{\mathrm{Pl}} + M_{\mathrm{MS}}\right)\left(d^2\mathbf{R}/dt^2 - \mathbf{g}_{\mathrm{ext}}\right), \qquad (1.12)$$

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

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

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

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:

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

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 *Carovilano 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

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

or for isotropic pressure

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

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

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

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

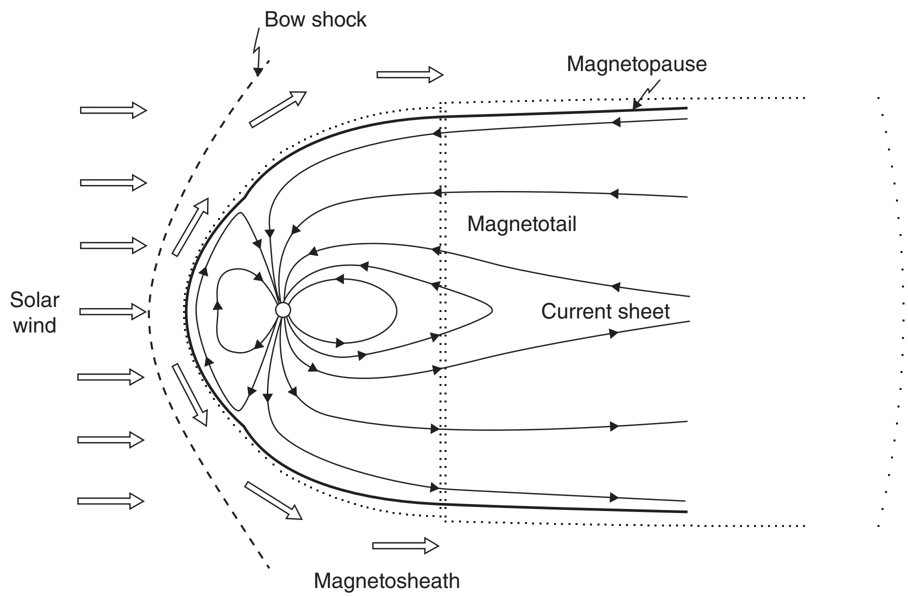

Figure 1.2 Same as Figure 1.1, with dotted lines added to show integration surfaces for discussion of stress balance.

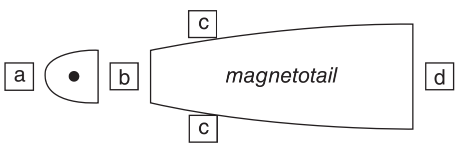

Figure 1.3 "Box model" representation of Figure 1.2 (see text for description).

the planet-facing boundary of the magnetotail) and joining it to a surface just outside the flanks and the top/bottom of the magnetotail, extended in the antisunward (solar-wind downstream) side as far as necessary to join it to the distant boundary where the magnetotail ends. (The reason for choosing the surfaces just outside the magnetic boundaries is discussed in section 1.4.) Both surfaces are indicated by dotted lines in Figure 1.2. To further simplify the discussion of global forces on enclosed volumes, Figure 1.3 shows these two volumes represented as boxes (planet surrounded by dayside magnetosphere on the left, magnetotail on the right), with the various interface/boundary surfaces labeled by letters:

a. Dayside magnetosphere boundary
b. Magnetosphere/magnetotail interface
c. Magnetotail flank boundaries
d. Magnetotail termination boundary

Surface (b) is the bounding surface introduced previously for the calculation of the force between the magnetotail and the dayside magnetosphere, equation 1.18. Surface (d) is the end of the stretched-out magnetic field configuration, discussed in section 1.3.3. The magnetotail problem is primarily about the $\hat{\mathbf{x}}$ components of the global forces acting on these volumes.

Forces acting on the dayside magnetosphere volume are F_a, the well-understood antisunward pressure force on the dayside magnetosphere exerted by the solar wind, and F_b, the antisunward tension force discussed above and given by $-F_{\mathrm{MT}}$ of equation 1.18, exerted by the magnetotail. There is thus a net antisunward force on the volume, or equivalently a continual transport into the volume of antisunward linear momentum, both from the solar wind on the dayside and from the magnetotail on the nightside. In accordance with the principle stated in section 1.3.1.1, this force is applied to the massive planet and adds antisunward linear momentum to it, ultimately balanced by solar gravity (the quantitative effect on the planet's orbit is, of course, utterly negligible; Earth's orbit is displaced by something like 0.1 mm).

Forces acting on the magnetotail volume include the same force $F_b = +F_{MT}$, now viewed as the sunward tension force exerted by the dayside on the magnetotail (or, equivalently, as transport of sunward linear momentum into the magnetotail from the dayside) across its planet-facing boundary, and in addition forces F_c and F_d across the sides and the distant boundary of the magnetotail, respectively. These are far from being understood; the very concept indeed of surface (d), the magnetotail termination boundary, is still somewhat nebulous (see section 1.3.3). Unlike the dayside magnetosphere, the magnetotail volume does not include the planet; its center of mass, however, although different from that of the planet, is not accelerated relative to the planet: The magnetotail as a structure is not blown away or otherwise removed by the forces acting on it, even though some of the plasma within it might be. By the already-mentioned principle of section 1.3.1.1, the total force on the magnetotail volume must therefore be essentially zero, which imposes a far-reaching constraint on F_c and F_d:

$$F_b + F_c + F_d \simeq 0; \tag{1.19}$$

equivalently, the sunward linear momentum that is transported into the magnetotail through its planet-facing boundary must be transported out through its boundaries elsewhere. Left unbalanced, the force F_b would collapse the magnetotail at roughly the Alfvén speed given by lobe magnetic field strength and plasma sheet density.

1.3.3. Termination of Magnetotail

Where and how the magnetotail ends in the downstream (antisunward) direction from the planet has not yet (to my knowledge) been observed unambiguously at any planet. Theoretically, there are several ways of defining the termination of the magnetotail and correspondingly several different definitions for the related concept of the length of the magnetotail. (*Caution*: It is not uncommon for papers to discuss "length of the magnetotail" without specifying which definition is meant.)

1.3.3.1. Closed Magnetosphere. The simplest case is that of a magnetically closed magnetosphere, where all the magnetic field lines that leave the planet return to the planet. The magnetic flux of the stretched-out field lines in one half of the magnetotail cross section must connect to that of the oppositely directed field lines in the other half, as one proceeds antisunward; since the total flux is finite, at some distance all of it has been connected and the magnetotail ends. (*Note:* "Connection" here refers to a property of the field configuration, "reconnection" to a physical process.) Although the length of the magnetotail is thus unambiguously defined, it is not uniquely determined: Its value obviously depends on the profile of the normal magnetic field component in the field reversal region. At one extreme, *Johnson* [1960], in his famous "teardrop" model, assumed that the magnetotail fields are confined within a surface that closes behind the planet at approximately the solar wind thermal speed, neglecting all interior stresses; this gives a distance from the planet to the end of the magnetotail about 5–20 times the distance to the dayside magnetopause. At the other extreme, *Dessler* [1964] assumed that the magnetotail fields, although closed in the sense of not connecting to an exterior medium, are (by the pressure of hydromagnetic waves generated in the solar wind interaction) kept open in the sense of not closing across the field reversal region; the magnetotail then extends indefinitely and ends only with the termination of the solar wind by interaction with the interstellar medium (thought then to occur at a heliocentric distance of some 20–50 AU but known now to be much farther out).

1.3.3.2. Open Magnetosphere. The case of an open magnetosphere is more complicated. A stretched-out field line can now connect either with the oppositely directed field in the other half of the magnetotail or with the magnetic field in the solar wind. The topology of an open magnetotail when the interplanetary magnetic field is parallel to the planet's magnetic dipole is illustrated schematically in Figure 1.4 for the entire system and in Figure 1.5 more specifically for the magnetotail. In both figures, the presentation is simplified: In Figure 1.5, the near-planet region is shown foreshortened in comparison to the rest (the segment to the left of the X line corresponds in reality to more than the full extent of Figure 1.1), and the deformation of the magnetic field by magnetosheath flow is not shown (outside the magnetotail the field lines are in reality tilted to the right, due to field line draping in the magnetosheath, and become vertical only after they cross the bow shock); Figure 1.4, intended to illustrate just the three-dimensional topology of magnetic field and plasma bulk flow, makes no pretense to realism in either scale or shape.

The most widely used definition for the length of an open magnetotail, proposed by *Dungey* [1965] and shown as $\mathscr{L}_{\mathrm{MT}}$ in Figure 1.4 and as $\mathscr{L}_c$ ("connected tail") in Figure 1.5, is given by solar wind speed multiplied by flow time across the open field line region (at Earth generally estimated from ionospheric plasma flow across the polar cap). It is often viewed as the distance to the last field line in the magnetotail connected to the planet (sometimes the length of the magnetotail is understood as the distance to the last *closed* field line in the magnetotail, which is the distance to the nightside X line in both figures). The magnetotail length defined by *Dungey* [1965], however, clearly is equal to the length of the open field line region *projected following magnetic field lines into the undisturbed solar wind*; the projected region is approximately a rectangle of length $\mathrm{L_{MT}}$ and width $\mathrm{L_X}$ (Figure 1.4), with $\mathrm{L_{MT}}\mathrm{L}_X\times$ interplanetary magnetic field = open magnetic flux. At Earth, empirical estimates give $\mathrm{L}_X << \mathrm{L_{MT}}$, implying a highly elongated rectangle described by *Stern* [1973] as "a long narrow 'window' along the geomagnetic tail." Furthermore, a stretched magnetic field configuration is possible even when the field lines are no longer connected to the planet, as shown over the distance L_d ("disconnected tail") in Figure 1.5.

For the purposes of this chapter, which discusses the problem posed by the tension force in the magnetotail, termination of the magnetotail is appropriately defined

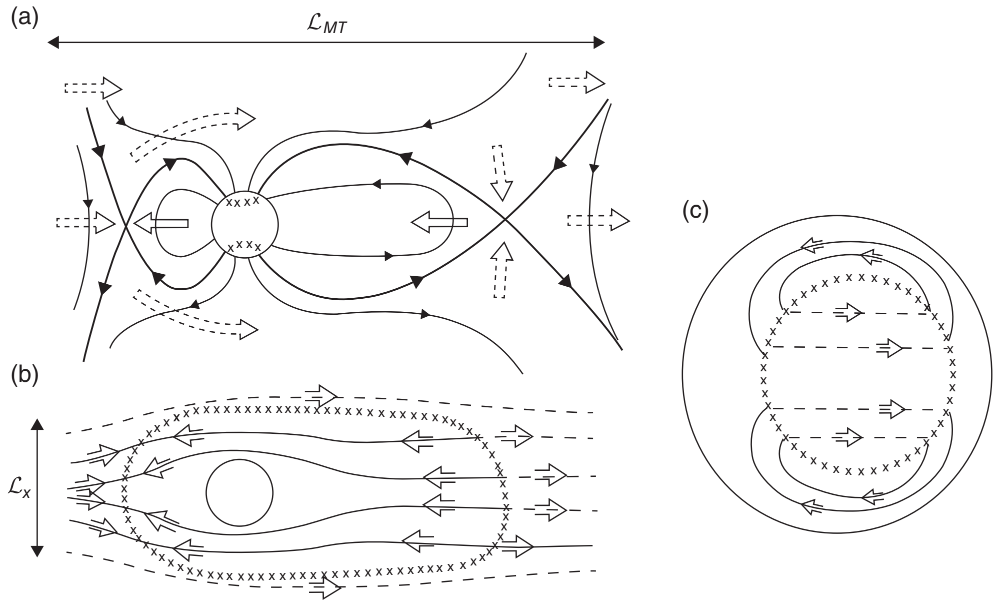

Figure 1.4 Schematic topological view of a magnetically open magnetosphere. (a) Noon-midnight meridian plane (solid lines: magnetic field lines, open arrows: plasma bulk flow directions). (b) Equatorial plane (lines: plasma flow streamlines, line of x's: magnetic X line = closed/interplanetary field line boundary). (c) Projection on ionosphere (lines: plasma flow streamlines, line of x's: open/closed field line boundary = projection of magnetic X line = polar cap boundary) [*Vasyliūnas*, 2011].

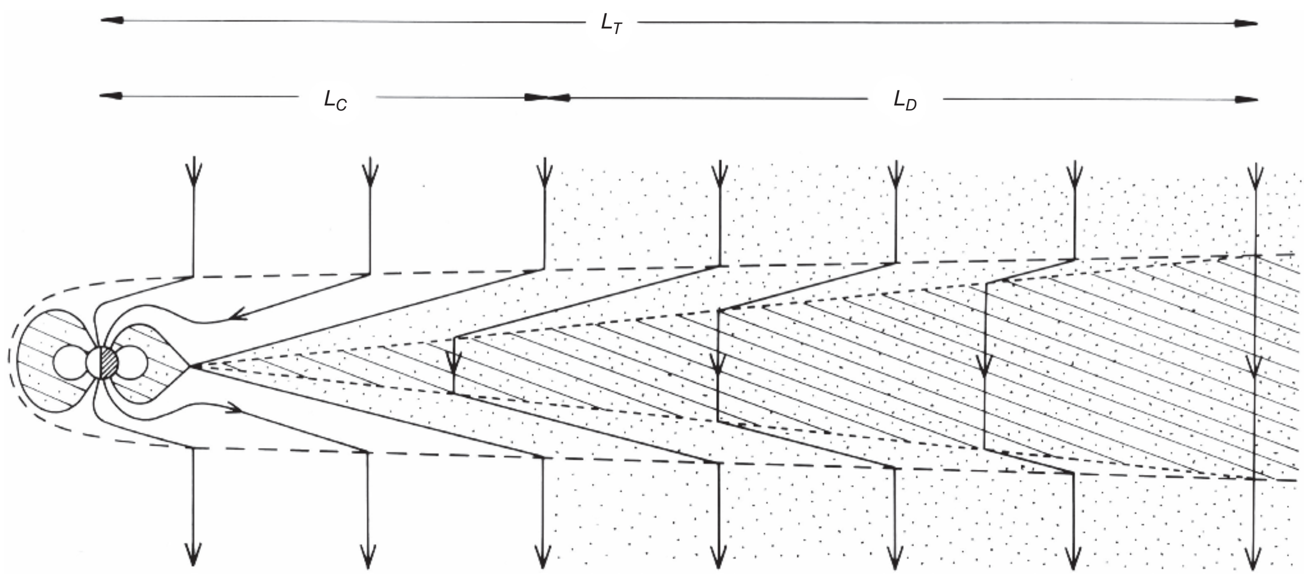

Figure 1.5 Sketch of the open magnetosphere and magnetotail in the noon-midnight meridian, showing magnetic field lines (solid lines), magnetopause (dashed line), and plasma sheet (dashed area) [from *Cowley*, 1991].

as the distance where that tension force is no longer present and no further antisunward transport of linear momentum need be accounted for. The tension force estimate of equation 1.18 applies for a cross section of the magnetotail not only at its interface to the dayside but also at all larger distances antisunward, as long as the twin properties of stretched antialigned ("tail like") magnetic fields and negligible plasma stresses hold. The magnetotail thus ends where (as, e.g., at distance L_d in Figure 1.5) the field components along the tail axis no longer are dominant, or the plasma stresses have become important over the entire cross section, or both.

1.4. WHAT MAINTAINS A MAGNETOTAIL?

The magnetotail problem in a nutshell is this: If the magnetotail is to be maintained as an enduring structure, neither collapsing nor being blown away, the net sunward magnetic tension force exerted on the magnetotail across its planet-facing boundary must be balanced by an equal antisunward net force across the remaining boundaries taken together. Alternatively, the sunward linear momentum transported into the magnetotail across its planet-facing boundary must be transported out (or, equivalently, an equal amount of antisunward linear momentum transported in) across the other boundaries: Linear momentum is a conserved quantity, and there is not sufficient mass in the magnetotail for storing it.

The necessary (but not sufficient) condition for maintaining a magnetotail is, from equations 1.18 and 1.19,

$$F_c + F_d \approx -\left(B_T^2/8\pi\right)\left(1-\delta\right)A_T. \tag{1.20}$$

With the use of equation 1.7 to express the force $F_c + F_d$ as an integral over the surfaces (c) and (d), noting that, with $\hat{\mathbf{u}} = \hat{\mathbf{x}}$, $\hat{\mathbf{n}}\cdot\hat{\mathbf{u}} = -1$ for surface (d), and with the assumption (for simplicity) that pressure is isotropic, condition (20) may be rewritten as

$$\begin{aligned}\left(B_T^2/8\pi\right)\left(1-\delta\right)A_T = &+\int_{b+c+d} dA\left\{\rho V_n V_x\right\} \\ &+\int_c dA\left\{\hat{\mathbf{n}}\cdot\hat{\mathbf{x}}\left(P+B^2/8\pi\right)-B_nB_x/4\pi\right\} \\ &-\int_d dA\left\{P+\left(B_t^2-B_n^2\right)/8\pi\right\}.\end{aligned} \tag{1.21}$$

In equation 1.21 the left-hand (LH) side (for convenience written positive by reversing all signs) is the magnetic tension force that is required to be balanced by what is on the RH side. The first term on the right is the bulk-flow stress integrated over the complete (closed) bounding surface of the magnetotail volume, including surface (b) on which the bulk flow stress is usually considered negligible but turns out to be significant in some models; the remaining terms are the pressure and magnetic tension on surfaces (c) and (d).

Equation 1.21 can be considerably simplified. The magnetic tension force on surfaces (c) and (d) may be assumed negligible: on (d) by definition of the surface and on (c) by choice of surface just outside the flanks of the magnetotail (a deliberate choice, as noted in section 1.3.2: accounting for the tension force of stretched field lines by ascribing it to magnetic tension at the outer boundaries of the volume would not solve the magnetotail problem but would merely displace it elsewhere). The bulk-flow-stress integral can be written, by partitioning the complete bounding surface into inflow ($V_n<0$) and outflow ($V_n>0$) segments, as the sum of two integrals:

$$\int dA\left\{\rho V_n V_x\right\} = S_{\text{out}}\left\langle V_x\right\rangle_{\text{out}} - S_{\text{in}}\left\langle V_x\right\rangle_{\text{in}}, \tag{1.22}$$

where

$$S_{\text{out}} \equiv \int_{V_n>0} dA\left|\rho V_n\right|,\quad S_{\text{in}} \equiv \int_{V_n<0} dA\left|\rho V_n\right| \tag{1.23}$$

and $\langle V_x\rangle_{\text{out}}$, $\langle V_x\rangle_{\text{in}}$ are the (suitably weighted) averages of V_x over the corresponding segments. By conservation of mass,

$$S_{\text{in}} - S_{\text{out}} = dM/dt, \tag{1.24}$$

where M is the magnetotail total mass; since M is small and slowly varying, dM/dt can be neglected and $S_{\text{in}} \simeq S_{\text{out}} \equiv S$ assumed as a reasonable approximation. Then

$$\int_{b+c+d} dA\left\{\rho V_n V_x\right\} = S\,\Delta V_x, \tag{1.25}$$

where $\Delta V_x \equiv \langle V_x\rangle_{\text{out}} - \langle V_x\rangle_{\text{in}}$. The quantity S (>0 by definition) is the total plasma mass flow through the magnetotail and its region of interaction with the solar wind and ΔV_x is the average change of velocity between inflow and outflow ($\Delta V_x > 0$ means net slowdown of antisunward or speedup of sunward flow).

Equation 1.21 is now now simplified to

$$\begin{aligned}\left(B_T^2/8\pi\right)(1-\delta)A_T \simeq &+S\Delta V_x \\ &+\int_c dA\left(\hat{\mathbf{n}}\cdot\hat{\mathbf{x}}\right)\,P - \int_d dA\;P,\end{aligned} \tag{1.26}$$

which states that what can balance the magnetic tension force (on the left) is (on the right) an appropriate velocity change of a mass flow through the magnetotail, plus the (external) pressure on the flanks as long as the magnetotail is flaring outward ($\hat{\mathbf{n}}\cdot\hat{\mathbf{x}} > 0$); the pressure on the distant outer boundary, to the contrary, acts in the same direction as the tension force at the inner boundary and hence cannot balance it, likewise the pressure on the flanks if $\hat{\mathbf{n}}\cdot\hat{\mathbf{x}} < 0$. (Internal pressure is discussed in Section 1.A.2.)

Solar wind pressure on the flaring flanks as a way to balance the magnetic tension force of the magnetotail was suggested by *Wentworth* [1967]. For any reasonable model of flaring, however, the effect is relatively small in comparison to what is needed; thus it is convenient to take it into account, along with all the other pressure terms, simply by redefining the correction term δ on the RH side [*Carovillano and Siscoe*, 1973]. Equation 1.26 is then further simplified to

$$\left(B_T^2/8\pi\right)\left(1-\delta\right)A_T \simeq S\Delta V_x \tag{1.27}$$

as the basic global stress balance condition.

1.4.1. Flow Patterns to Maintain Magnetotail

The requirement for maintaining the magnetotail has now been reduced to having a plasma flow *through* the magnetotail (input ≃ output), inflowing and outflowing plasma having different average velocities, with the amount of mass flowing through and the velocity change between inflow and outflow corresponding to a linear momentum change rate that balances the magnetic tension force, in accordance with equation 1.27. Three types of flows which have been discussed in this context are sketched in the three panels of Figure 1.6. Each panel represents the magnetotail box of Figure 1.3, and the solid arrows at the boundaries show inflow and outflow, with flow speed indicated qualitatively by lengths of arrows. Dotted lines inside the box, meant to suggest flow lines within the magnetotail, are for orientation only: The linear momentum change within the entire volume is determined completely by inflow and outflow values on the enclosing boundary surface. The three flow systems are:

1. Inflow from magnetosheath along open magnetic field lines (Dungey cycle)
2. Boundary layer flow on closed field lines (Axford-Hines circulation/magnetospheric convection)
3. Plasma outflow from sources internal to the magnetosphere (planetary wind, Vasyliūnas cycle).

Sections 1.4.1.1, 1.4.1.2, and 1.4.1.3 describe each of the flows in more detail:

a. The underlying physical process and what can be said about its quantitative aspects
b. Transport of linear momentum (where does it come from, and where does it go?)
c. Questions of magnetic field topology and magnetic flux transport.

1.4.1.1. Inflow on Open Field Lines. Magnetotail formation is most easily understood in the case of a magnetically open magnetosphere [*Dungey*, 1961]. Reconnection of the planet's magnetic field with the interplanetary magnetic field at the dayside magnetopause forms flux tubes of open magnetic field lines, which are then pulled

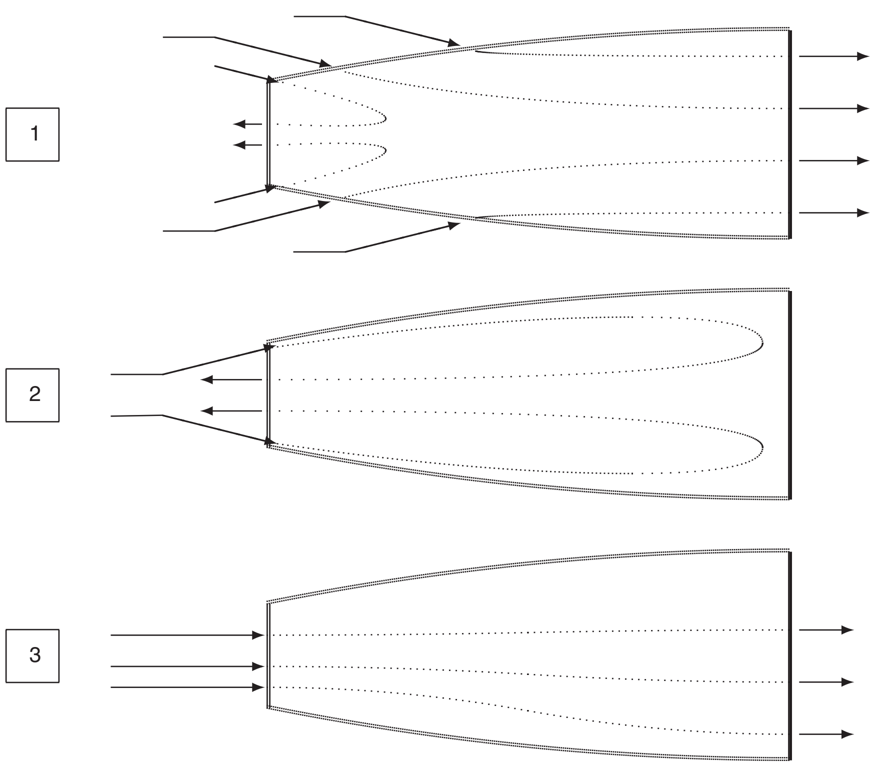

Figure 1.6 Possible flow patterns that provide stress to maintain magnetotail, described in text.

downstream by solar wind flow while remaining attached to the planet, thereby producing the highly stretched field configuration, until at some distance on the nightside the oppositely directed fields from the two hemispheres of the planet reconnect, forming on one side (sunward of the reconnection distance) flux tubes of closed field lines that flow back toward the planet, and on the other side flux tubes of interplanetary field lines that continue flowing with the solar wind. The topology has been sketched here in Figures 1.4 and 1.5.

The associated plasma flow system which accounts for stress balance is shown schematically in panel 1 of Figure 1.6; the view is in the midnight meridian. Magnetosheath (solar wind) plasma flows into the magnetotail along open magnetic field lines, predominantly at the top and bottom boundaries (plasma mantle), and then flows out, most of it downstream with the solar wind but part of it sunward. The boundary between the magnetosheath and the magnetotail in the plasma mantle region can be described to first approximation as rotational discontinuity plus slow-mode expansion fan [*Siscoe and Sánchez*, 1987; *Sánchez et al.,* 1990; *Siscoe et al.*, 1994]. The mass inflow $S=\int dA\rho V_n$ can then be related to the open magnetic flux $\Phi_{\text{open}}=\int dA\, B_n$ by noting that the plasma flow component normal to a rotational discontinuity equals the Alfvén speed calculated from the normal component of the magnetic field:

$$S = \int dA\ \rho\, B_n \left(4\pi\rho\right)^{-1/2} \approx \Phi_{\text{open}} \left(\rho / 4\pi\right)^{1/2} \qquad (1.28)$$

The velocity decrease across the boundary is given approximately by the Alfvén speed calculated from the interior (magnetotail) field B_T and the exterior density $\rho(\sim\rho_{\text{sw}}$ in order of magnitude):

$$\Delta V_x \approx B_T (4\pi\rho)^{-1/2}. \qquad (1.29)$$

Equations 1.28 and 1.29 show that the quantitative contribution from solar wind plasma inflow along open field lines to magnetotail stress balance is

$$S\,\Delta V_x \approx \Phi_{\text{open}}\, B_T/4\pi, \qquad (1.30)$$

and comparison with equation 1.27 implies that this is adequate to maintain the magnetotail if

$$\Phi_{\text{open}} \approx B_T A_T (1-\delta)/2. \qquad (1.31)$$

The required amount of mass inflow, estimated from equations (1.29)–(1.31) and normalized to solar wind mass flux through area A_T, is

$$S/\rho_{\text{sw}} V_{\text{sw}} A_T \sim \xi\ B_T \left(8\pi\rho_{\text{sw}} V_{\text{sw}}^2\right)^{-1/2} \qquad (1.32)$$

[*Vasyliūnas*, 1987], where

$$\xi \equiv \left(\rho_{\text{sw}}/\rho\right)^{1/2} (1-\delta)/\sqrt{2} \sim O(1). \qquad (1.33)$$

The transport of linear momentum in this process is straightforward. Antisunward linear momentum of magnetosheath flow is carried into the magnetotail, predominantly through its top and bottom boundaries, by the inflowing plasma; reduction of the velocity corresponds to transfer of some antisunward momentum from bulk flow to tension of magnetic field lines, which then carry the antisunward momentum into the dayside magnetosphere and ultimately to the planet.

This process of maintaining the magnetotail is well understood qualitatively; its theory has been developed to the point of providing quantitative relations such as those discussed above and at least at Earth has proved quite useful for interpreting data and consistent with much that is observed. For this reason and also because Dungey's open-magnetosphere model is supported by many other observations (particularly the dependence of geomagnetic activity on the interplanetary magnetic field), the open-magnetosphere concept of the magnetotail is widely considered as the most likely or even as *the* explanation. Nevertheless, it is subject to some important limitations:

a. The process relies on reconnection between magnetic fields on the two sides of the magnetopause, which depends strongly on the (highly variable) orientation of the interplanetary magnetic field relative to the planet's magnetic dipole. It is not entirely clear how the magnetotail is to be maintained during a prolonged period of unfavorable relative orientation.
b. Although the theory of this magnetotail model is arguably more advanced than that of any other so far, it is to my knowledge still not capable of predicting from first principles even approximate values for key parameters of the open magnetosphere, such as open flux Φ_{open} or magnetotail length $\mathscr{L}_{\text{MT}}$ (whereas the Chapman-Ferraro theory *can* predict, e.g., the approximate distance to the dayside magnetopause). There is no well-established answer even to the basic question whether the configuration of the open magnetosphere is uniquely determined by solar wind parameters in a steady state [*Vasyliūnas*, 2011].

Once an open flux tube has been formed by reconnection at the dayside magnetopause, how far can it be carried downstream by the solar wind before it reconnects in the magnetotail with its partner from the other hemisphere? In the conventional quasi-steady-state view of

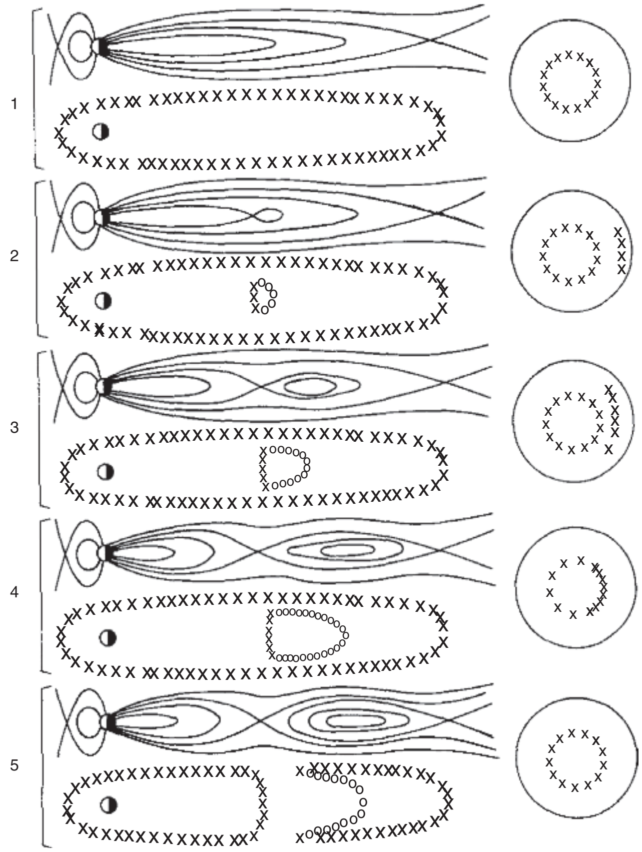

Figure 1.7 Possible changes of the magnetic field topology in the magnetotail of an open magnetosphere [*Vasyliūnas*, 1976]. Each panel has the format of Figure 1.4.

the Dungey cycle (as in Figure 1.4), magnetotail reconnection occurs at an X line, the location of which, although difficult to predict, is assumed to remain more or less fixed. It is, however, conceivable that the solar wind might continue carrying the entire distant magnetotail configuration (X line and all) downstream with itself, stretching the magnetotail indefinitely. Consideration of what might happen in such an extreme limit was what led to the concept of topological changes ("plasmoid" evolution) shown in Figure 1.7 [*Vasyliūnas*, 1976], although the concept was published from the outset as a model for magnetospheric substorms [see historical note in *Vasyliūnas,* 2011]; particularly as reformulated by *Hones* [1976, 1977], it became one of the most widely discussed (and disputed!) models for the magnetospheric substorm at Earth, subsequently applied extensively also to interpret analogous/similar dynamical events in the magnetospheres of other planets [e.g., *Syrjäsuo and Donovan*, 2007; *Hill et al.*, 2008; *Jackman et al.*, 2011].

Magnetotail dynamical events per se are beyond the scope of this chapter, but the plasmoid model does suggest an alternative form of the Dungey cycle, in which (differently from the conventional steady-state picture of magnetic flux and plasma circulating together between dayside and nightside reconnection regions) there is no direct return of the magnetic flux: Once reconnected at the dayside magnetopause, open flux tubes are carried away by the solar wind flow, total magnetic flux of the planet being conserved by creating, at a newly formed near-planet X line (Figure 1.7), the necessary return flux together with an equal amount of oppositely directed flux that flows away with the solar wind. What one effectively then has, on the average, is circulation of magnetic flux that need not be coupled to circulation of plasma; the amount of plasma in the return flow can in principle be as small as desired. Such a model may be relevant to, e.g., magnetospheric so-called sawtooth events at Earth [e.g., *Huang et al.*, 2009, and references therein] as well as to the controversial question of plasma return flow at Jupiter [*McComas and Bagenal*, 2007, 2008; *Cowley et al.*, 2008]. For this chapter, its main interest lies in the application of the concept to models (e.g., section 1.4.1.3) in which plasma return flow may be excluded.

1.4.1.2. Boundary Layer Flow. Almost simultaneously with the proposal of the open magnetosphere by *Dungey* [1961], *Axford and Hines* [1961] proposed a more general concept of a *viscous-like interaction* (also called *tangential drag*) at the magnetopause. In their own words: "By this we mean simply that some of the momentum of the solar wind is transferred across the boundary of the magnetosphere to the ionization within. The nature of this momentum transfer is, for present purposes, of minor importance; its existence, or the existence of an equivalent mechanism, is crucial." The essential new result put forward by *Axford and Hines* [1961] was a pattern of plasma circulation, universally known as magnetospheric convection. Of its possible causes, viscous-like interaction was only one of several mentioned, including the open field line model of *Dungey* [1961]; in subsequent comments on their paper, *Hines* [1974, 1993] emphasized that they had committed themselves neither to the viscous drag mechanism nor to the closed magnetosphere as the only options. Some years later, *Axford* [1969] had come to view magnetic reconnection rather than viscous drag as the dominant mechanism.

One signature of magnetospheric convection driven by viscous-like interaction (defined by *Axford* [1969] as "momentum transfer without field-line reconnection") in a closed magnetosphere is antisunward plasma flow in regions just inside the magnetopause, connected to sunward flow deeper inside the magnetosphere. By contrast, in the geometrically simplest open magnetosphere, plasma flow is sunward everywhere within the closed field line region, antisunward flow driven by tangential stress of reconnected field lines occurring only on open field lines (see Figure 1.4); more complicated geometries which contain antisunward flows in some closed field line regions may be envisaged [*Vasyliūnas*, 1984], but they require placing reconnection at unconventional sites. The observational identification at Earth of the so-called low-latitude boundary layer [*Hones et al.*, 1972, *Eastman et al.*, 1976, 1985; *Haerendel et al.*, 1978, and others] adjacent to and inside the magnetopause (on what are presumed to be, in all probability, closed field lines), with pronounced antisunward flow and with plasma properties intermediate between those of magnetosheath and magnetosphere, has revived interest in viscous-like interaction as an alternative to magnetic reconnection for, or at least a contributor to, driving magnetospheric convection and maintaining the magnetotail [*Rostoker*, 1987]. More recently, it has been argued that viscous-like interaction may be important in the magnetosphere of Jupiter [*Delamere and Bagenal*, 2010, and references therein].

The plasma flow system that could account for stress balance in the magnetotail of a magnetically closed magnetosphere is that sketched in panel 2 of Figure 1.6; the view is now in the equatorial plane. Antisunward-flowing plasma of the magnetopause boundary layers enters the magnetotail volume at the flanks, is eventually turned around, and flows back to the dayside magnetosphere in the middle. The transport of linear momentum in this process follows a path similar to that in the open magnetosphere (section 1.4.1.1). Antisunward linear momentum of magnetosheath flow is carried across the magnetopause, in this case by the tangential drag process and predominantly through the flanks, going into the antisunward flow of the plasma in the boundary layers; deceleration and ultimate reversal of the velocity correspond to transfer of all the antisunward momentum from bulk flow to tension of magnetic field lines, which then carry the antisunward momentum into the dayside magnetosphere and ultimately to the planet (the sunward linear momentum of the return flow implies an even larger magnetic tension but does not change the net amount of linear momentum going into the dayside magnetosphere).

The antisunward flow speed in the boundary layer may reasonably be equated to a significant fraction of magnetosheath flow speed (since the linear momentum is assumed to be supplied directly across the magnetopause, albeit by an unspecified mechanism), and since the flow is ultimately reversed, the velocity change ΔV_x may be assumed to be of a similar order of magnitude. For a given mass flow S, boundary layer flow is thus more efficient in maintaining stress balance than inflow along open field lines, for which ΔV_x given by equation 1.29 is in general considerably smaller than the flow speed in the exterior medium. On the other hand, since the boundary layers are (almost by definition) much smaller than the cross-sectional area of the magnetotail, S here is likely to be considerably smaller than the open-magnetosphere S from equation 1.28. Furthermore, S in the boundary layer eventually flows into the dayside magnetosphere and contributes to its mass source, whereas most of the open-magnetosphere S can flow out into the solar wind again, with only a small fraction contributing to the mass budget of the dayside magnetosphere.

Obtaining theoretical estimates of mass flow S in the boundary layer presupposes having at least a rough semiquantitative model of the viscous-like interaction. At present, however, there is no agreement even on what physical process constitutes the mechanism of tangential drag. Possibilities suggested at various times include cross-field diffusion by scattering from waves, diffusion by MHD turbulence, localized direct penetration, Kelvin-Helmholtz instability of the magnetopause (which has recently received particular attention [*Delamere and Bagenal*, 2010]), and others. A reliable estimate of $S \Delta V_x$, to determine the contribution of boundary layer flow to magnetotail stress balance, is thus extremely difficult.

Magnetic field topology should not present any difficulties in this process: Field lines remain closed as they are stretched in the boundary layer and contract in the return flow. Constraints on the maximum extent of this magnetotail may be imposed, however, by pressure changes from the expanding and contracting flux tube volumes [*Erickson and Wolf*, 1980; *Kivelson and Spence*, 1988, and others].

1.4.1.3. Outflow from Interior Source. Magnetospheres of the giant planets (Jupiter and Saturn) differ from those of the terrestrial planets (Earth and Mercury) in two significant respects [see, e.g., review by *Bagenal*, 2009, for a comparative survey]:

1. Rotational effects are more important, because of both the faster rotation of the planet and the larger size (in kilometers as well as in planetary radii) of its magnetosphere, posing the problem of what radial force (if any) can sustain the centripetal acceleration of corotating plasma.
2. Mass input to the magnetosphere is primarily from sources deep within the magnetosphere, specifically from moons of the planet (Io at Jupiter, Enceladus at Saturn), posing the problem of where does the added mass go.

Hill et al. [1974] and *Michel and Sturrock* [1974] proposed that, at a rapidly rotating planet, magnetospheric plasma can always be maintained in (at least approximate) corotation on the dayside by the constraining action of solar wind pressure, but on the nightside, once the magnetic field has become too weak to exert a sufficiently large radial tension force, the plasma can flow out down the magnetotail, forming what they called the "planetary wind." Although proposed before the interior (planetary-moon) mass sources in the magnetosphere were discovered, this concept provides an obvious mechanism for the added mass to go away: It can flow out with the planetary wind. (Plasma transport in the inner magnetosphere, from the source region to the distance where the planetary wind begins, is a separate problem, difficult and much studied but beyond the scope of this chapter.)

This plasma flow system can be invoked to account (at least in part) for stress balance of the magnetotail, as sketched in panel 3 of Figure 1.6; the view is in the equatorial plane. Antisunward-flowing plasma of the planetary wind enters the magnetotail volume through the planet-facing boundary and eventually exits, with reduced speed, through the distant boundary (or possibly through the flanks). The transport of linear momentum is now somewhat different from that in sections 1.4.1.1 and 1.4.1.2: The antisunward linear momentum no longer comes from the solar wind flow but from the planet, which acquires an equal amount of sunward linear momentum (through the force that accelerates to corotation the plasma that is then lost to the planetary wind; it is a force and not just a torque because outflow is predominantly on the dusk side, as suggested in the figure). Deceleration of the outflow corresponds to transfer of part of the antisunward momentum from bulk flow to tension of magnetic field lines; these then carry the antisunward momentum into the dayside magnetosphere and ultimately to the planet, where it subtracts from the sunward momentum acquired by the planet in the flow acceleration process mentioned above. The net sunward linear momentum transported into the planet from the magnetotail equals the antisunward momentum remaining in the outflow after it has exited the magnetotail (simple physical analog: think of the planet-plus-magnetotail system as the rocket and the distant outflow as the rocket's exhaust).

The amount of mass supplied to the magnetosphere by a planetary-moon source is determined almost entirely by the properties of the moon and by its interaction with the surrounding medium, taking into account both physical and chemical processes. For Io at Jupiter and Enceladus at Saturn, the input rates are reasonably well determined by a combination of empirical data and modeling [see, e.g., review by *Bagenal and Delamere*, 2011, and references therein]. Under the assumption that most of the plasma ultimately gets out through the magnetotail, the value of S is given thereby. The value of ΔV_x, however, remains unknown: At present, it is difficult enough to determine from observations the mean value of the outflow speed, let alone its change with distance, and theory for ΔV_x is virtually nonexistent. Determining the relative contribution to magnetotail stress balance is thus even more difficult for the interior-source outflow than for the boundary layer flow of section 1.4.1.2.

Planetary wind outflow presents a problem of magnetic topology. At both Jupiter and Saturn, the source of plasma lies deep within the magnetosphere, in the region of esentially dipolar magnetic field lines, and mass ouflow carries net magnetic flux with it; furthermore, the outflow represents a net loss from the system, not a circulation. While the mass loss is negligible in relation to the total mass, the accompanying removal of magnetic flux is not: e.g., at the estimated present plasma source rate from Io, a fraction $\sim O(10^{-3})$ of Io's mass would be removed over the age of the solar system, but the equivalent of the entire magnetic flux from one hemisphere of Jupiter's surface would be removed in roughly a year. Clearly, magnetic flux must return even as plasma does not. The simplest topological configuration that accomplishes this was suggested by *Vasyliūnas* [1983], in a much-cited figure shown here as Figure 1.8. The basic model is essentially that discussed already in connection with the Dungey cycle in section 1.4.1.1 and illustrated in Figure 1.7; the same topological sequence is shown as function of local time in panels 1–4 of Figure 1.8, and as a function of elapsed time in panels 1–4 of Figure 1.7 (this is in fact how Figure 1.8 was actually derived).

1.4.2. Hybrid Models

One may speak of hybrid models in two senses: combining different models, i.e., having the magnetotail maintained by several processes acting simultaneously, or modifying one model by including in it features from another.

Combination of flow patterns 1 and 2 (inflow on open field lines, and boundary layer flow) is possible without much complication and has long been discussed for Earth's magnetosphere. The relative importance of the two in accounting for the magnetotail depends partly on the question, what fraction of the magnetic flux in the lobes of the magnetotail is open flux created by dayside reconnection and what fraction is closed flux transported into the tail by boundary layers?

Combination of flow patterns 1 and 3, i.e., inflow on open field lines (Dungey cycle) and outflow from interior sources (Vasyliūnas cycle), is also possible but somewhat more complicated and subtle [*Cowley et al.*, 2003; *Vasyliūnas*, 2007b].

Combination of flow patterns 2 and 3, i.e., boundary layer flow driven by viscous-like interaction on closed field lines and outflow from interior source, faces the problem of how to reconcile the return flow, which is an essential part of pattern 2, with the outward flow, which is an equally essential part of pattern 3.

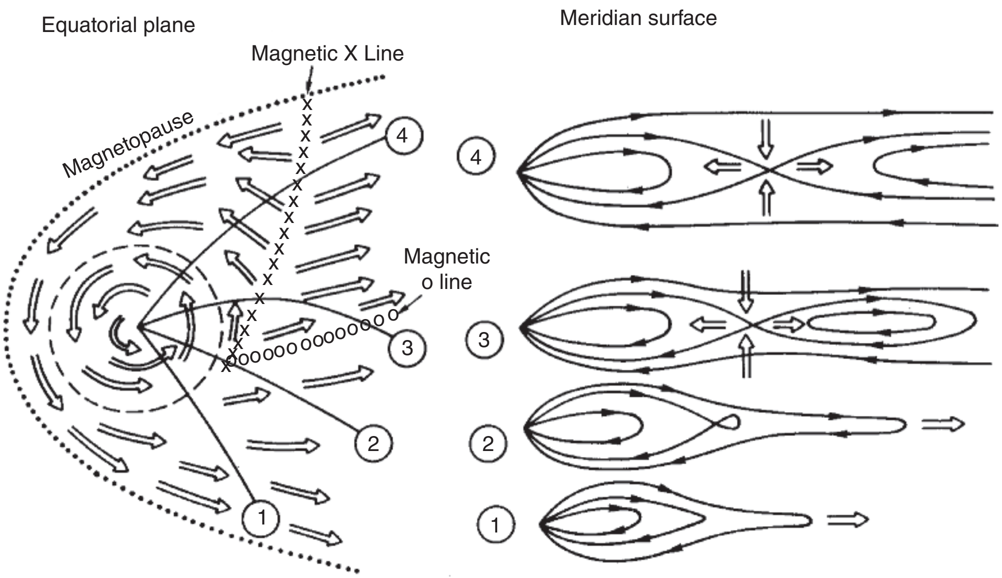

Figure 1.8 Qualitative sketch of planetary wind flow and magnetic topology [*Vasyliūnas*, 1983]. Magnetic field directions are appropriate for Jupiter.

It is possible, at least in principle, to modify the boundary layer model so as to remove the return flow: Assume that boundary layer flow carries too much linear momentum to be turned back by magnetic field tension and continues to flow antisunward indefinitely, breaking open the closed magnetic field lines the same way as outflow from an interior source, by the topological sequence of Figures 1.7 and 1.8. With this modification, flow pattern 2 could be combined with 3. Particularly for Jupiter, an interesting possibility might be: on the dawn side, boundary layer outflow driven by tangential drag from the solar wind; on the dusk side, rotationally driven outflow from the internal (Io) source.

1.5. CONCLUSION

The fundamental problem of the magnetotail is how to maintain the configuration of highly stretched magnetic field lines within low-density lobes, separated by a relatively thin field reversal region and plasma sheet. Such a configuration implies a magnetic tension force at the inner (planet-facing) boundary of the magnetotail, exerted ultimately on the massive planet, which must be balanced by a tension-like force at the outer boundary, and the question is, what is the nature and origin of this force? Equivalently, the force at the inner boundary represents sunward linear momentum flowing into the magnetotail, which (to conserve momentum) must be balanced by inflow of antisunward linear momentum, represented by the force at the outer boundary.

Comparing terms in the integrated stress balance equation shows that the required force can only be provided by the velocity change of an appropriate mass flow-through. There are several qualitative conceptual models for this: (1) solar wind plasma entry on open field lines, slowed down (slightly) by magnetic force, (2) boundary layer flow, produced by (unspecified) tangential drag from the magnetosheath, with field lines pulled out until the flow is stopped and reversed, and (3) outflowing plasma from a source in the interior of the magnetosphere, slowed down by stretched field lines.

Concept 1 is generally considered the dominant explanation of Earth's magnetotail (at least during periods of significant geomagnetic disturbances) and has been widely applied, with or without adequate justification, to interpret observations of other magnetotails. It depends sensitively on orientation of the interplanetary magnetic field relative to the planetary magnetic dipole; the expected dependence is in agreement with many observations at Earth but, for lack of suitable observations, is difficult to check at other planets.

Concept 2 has been proposed for Earth, particularly during prolonged periods with a northward component of the interplanetary magnetic field, and recently has been receiving increasing consideration for Jupiter. As a potential explanation of magnetotails, however, concept 2 has been little studied (although the concept itself has received much attention as an alternative to magnetic reconnection), and concept 3 hardly at all.

Theoretical understanding is more advanced for concept 1 than for the others, but none have yet been developed into a quantitative theory. Quantitative properties of the open magnetosphere and magnetotail (open flux, length of reconnection line, effective length of magnetotail) have been related empirically to solar wind parameters, and quantitative properties of other models (boundary layer thickness, mass transport rates, flow profiles) have been empirically estimated, but for none of these are there as yet any real theoretical predictions (first-principles or otherwise).

APPENDIX: SOME QUESTIONS ABOUT INTERNAL PRESSURE

1.A.1. Plasma Sheet Effects on Global Tension Force

Plasma pressure plays a direct role in the local stress balance of the magnetotail [e.g., *Rich et al.*, 1972; *Siscoe*, 1972]. For the global stress integrals taken over the full cross section of the magnetotail, equation 1.16 or 1.17, the effects of the plasma pressure as well as the reduction of magnetic field within the plasma sheet from its value in the lobes are in general relatively small compared to the total. Hence it is useful to represent the integral as calculated from lobe values only, minus a correction term δ. Some sample estimates for δ, for isotropic pressure:

a. Ratio $\beta = 8\pi P/B^2$ assumed constant over the thickness of the plasma sheet [*Carovillano and Siscoe*, 1973]:

$$\delta = 2\left(A_{\mathrm{ps}} / A_T\right)\beta / (1+\beta)$$

b. Magnetic field within plasma sheet assumed to decrease linearly from B_T at the plasma sheet boundary to zero at the field reversal:

$$\delta = 8A_{\mathrm{ps}}/3A_T$$

In the above, A_{ps} and A_T are the cross-sectional areas of the plasma sheet and of the entire magnetotail, respectively.

1.A.2. Can Internal Pressure Maintain a Magnetotail?

In this chapter, I have repeatedly emphasized the exclusive role of the external forces in the global stress balance of the magnetotail. It might be asked: Why can't internal pressure maintain a magnetotail, simply by inflating the magnetic field? Don't some papers speak of internal pressure breaking the field open to make a magnetotail?

The problem of making a magnetotail by inflating the field is that the magnetotail exerts a tension force on the planet, and by Newton's third law the planet then exerts an *equal* force on the magnetotail, but the mass of the planet is enormously larger than the mass of the magnetotail, and hence the magnetotail will be accelerated right into the planet! In the absence of other forces, such collapse can be avoided only if the pressure in the magnetotail impacts *directly* on the planet's surface (or if the inflation is axially symmetric, as in a ring current, so that the forces from all directions cancel).

What is really described when one talks about making a magnetotail by "breaking open" the magnetic field as a result of internal pressure is not *maintaining* the magnetotail but *creating* it in time: An initial high pressure, in the process of breaking the field lines, creates a flow, which is what subsequently maintains the magnetotail.

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