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Interpretation of high speed flows in the plasma sheet

Chen, Chuxin, M.S.

Rice University, 1994

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**300 N. Zeeb Rd.
Ann Arbor, MI 48106**

RICE UNIVERSITY

INTERPRETATION OF HIGH SPEED FLOWS
IN THE PLASMA SHEET

by

CHUXIN CHEN

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

APPROVED, THESIS COMMITTEE

Richard A. Wolf, Chairman
Professor of Space Physics and Astronomy

Thomas W. Hill,
Distinguished Faculty Fellow, Space Physics
and Astronomy

Barry F. Dunning,
Professor of Space Physics and Astronomy

Houston, Texas

October, 1993

ABSTRACT

Interpretation of High Speed Flows in the Plasma Sheet

by

Chuxin Chen

Pursuing an idea suggested by *Pontius and Wolf* [1990], we propose that the “bursty bulk flows” observed by *Baumjohann et al.* [1990] and *Angelopoulos et al.* [1992] are “bubbles” in the Earth's plasma sheet. Specifically, they are flux tubes that have lower values of $pV^{5/3}$ than their neighbors, where p is the thermal pressure of the particles and V is the volume of a tube containing one unit of magnetic flux. Whether they are created by reconnection or some other mechanism, the bubbles are propelled earthward by a magnetic-buoyancy force, which is related to the interchange instability. Most of the major observed characteristics of the bursty bulk flows can be interpreted naturally in terms of the bubble picture. We propose a new “stratified fluid” picture of the plasma sheet, based on the idea that bubbles constitute the crucial transport mechanism. Results from simple mathematical models of plasma-sheet transport support the idea that bubbles can resolve the pressure-balance inconsistency, particularly in cases where plasma-sheet ions are lost by gradient/curvature drift out the sides of the tail or bubbles are generated by reconnection in the middle plasma sheet.

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I. INTRODUCTION

In this introduction, some background knowledge is presented. Then various previous work on the subject is summarized, and the direction of the present work is introduced.

A. Plasma Regions in Space

Some plasma regions near the Earth are shown in Figures 1 and 2. Figure 1 is a view of the noon-midnight meridian plane, which contains the Sun and the magnetic dipole axis of the Earth. Figure 2 shows the magnetic equatorial plane, i.e., a plane perpendicular to the Earth's magnetic dipole axis.

We start our introduction at the Sun, the ultimate source of the electromagnetic phenomena around the Earth. Hot gas escapes from the Sun and flows radially outward, carrying magnetic field with it. In interplanetary space, this gas forms a supersonic magnetized plasma flow called "SOLAR WIND". The "INTERPLANETARY MAGNETIC FIELD" (IMF), the magnetic field in the solar wind, intersects with the Earth at an average angle of 45 degrees relative to the Sun-Earth line. High variability is an important characteristic of the IMF; it makes geomagnetic activity interesting and difficult to predict. The direction of the IMF varies with position and time.

The Earth's intrinsic magnetic field, which can be approximately represented by a magnetic dipole, forms an obstacle in the solar wind flow. The magnetized plasma in the solar wind cannot penetrate the domain occupied by the Earth's magnetic field. This region is called the Earth's "MAGNETOSPHERE". Facing a supersonic plasma flow, a stationary shock wave, called the "BOW SHOCK" in this case, is naturally formed in front of the magnetosphere. The bow shock turns the supersonic flow into a subsonic one, which diverts around the magnetosphere. Dynamic processes in the bow shock transform the flow energy of the plasma into thermal energy. The gas is hotter and denser after passing

Figure 1. Plasma regions viewed in a noon-midnight meridian plane.

the bow shock than it was in the original solar wind.

The region between the bow shock and the magnetosphere is the "MAGNETOSHEATH", which consists of hot and dense plasma that has passed through the bow shock. The magnetic field in the magnetosheath is the shocked IMF. The "MAGNETOPAUSE", the boundary of the magnetosphere, separates the Earth's magnetic field from the IMF. But open field lines, which connect the Earth and the IMF, can pass through it. Particles from the magnetosheath can reach the "POLAR CUSP" along the open field lines. The magnetopause thus partially shields the magnetosphere from the solar wind plasma and the IMF.

The dayside magnetosphere extends to about 10 Earth radii (R_E) against the force of the solar wind, while on the nightside, the solar wind pulls the Earth's magnetic field into the shape of a long tail, called the "MAGNETOTAIL". The magnetotail extends at least a few hundred R_E . Just inside the magnetopause, there are two boundary layers, located at different latitudes. One is the "LOW LATITUDE BOUNDARY LAYER", which forms at lower latitude and probably consists of closed field lines. The flow in this layer is antisunward, in the same direction as the neighboring flow in the magnetosheath. It is like a viscous boundary layer. The other region is the "PLASMA MANTLE", which is located at higher latitude and forms on open field lines. The particles in the plasma mantle are mainly low energy ions and electrons. The solar wind in the magnetosheath pulls the open field lines through this region in the antisunward direction. The plasma flow in the mantle is approximately in the same direction, with a significant velocity component along the magnetic field line.

The "TAIL LOBE" is the region inside the plasma mantle. It contains highly ordered magnetic field and it is nearly devoid of plasma. The "PLASMA SHEET" is the region located between the north magnetotail lobe and the south magnetotail lobe. It is populated with hot plasma and it supports the current that changes the magnetic field direction from

Figure 2. Plasma regions viewed in the Earth's magnetic equatorial plane. The hollow arrows indicate the flow velocity.

sunward in the north tail lobe to antisunward in the south tail lobe. The energy densities of plasma and the magnetic field are of the same order of magnitude, and consequently the dynamics of the plasma sheet is dependent on both plasma and magnetic field. The center of the plasma sheet is called the "NEUTRAL SHEET", even though the magnetic field is not exactly zero there. The region between the plasma sheet and the tail lobe is the "PLASMA SHEET BOUNDARY LAYER". The plasma flows in this layer consist of two streams, sunward and antisunward. This layer provides a likely source for the plasma sheet plasma, although the mechanism that turns the high kinetic energy flows into the hot, slow flow of the plasma sheet remains to be established.

The "PLASMASPHERE" and the "VAN ALLEN BELTS" form the inner part of the magnetosphere. The plasmasphere contains plasma that has escaped from the ionosphere, while the Van Allen Belts consist of hot and much less dense plasma. Both regions are centered at the Earth. Most of the plasma particles drifting from the distant plasma sheet cannot enter these two regions, but flow around the inner magnetosphere to the dayside magnetopause.

B. Magnetospheric Convection

The plasma flow observed in the upper ionosphere is generally antisunward over the polar cap and sunward in the auroral zone. Such a flow pattern implies a circulation in the magnetosphere, i.e., the outer part of the magnetosphere moves in an antisunward direction, while the interior of it moves in a sunward direction. Two classic models were proposed many years ago to explain the convection. One is the closed model of *Axford and Hines* [1961], and the other is the open model of *Dungey* [1961].

The closed model is based on the assumption that the magnetic field lines of the magnetosphere are all closed. The magnetic field lines in the polar cap connect to the outermost part of the magnetosphere. A viscous interaction between the antisunward

moving solar wind in the magnetosheath and the magnetospheric plasma particles results in magnetic flux and plasma moving antisunward in the region adjacent to the magnetopause. The low latitude boundary layer is like such a viscous layer, since the flow in it is in the antisunward direction. In a steady state, the conservation of magnetic flux requires a return flow in the interior of the magnetosphere, i.e., a sunward flow in the plasma sheet. Direct measurements in the low latitude boundary layer, which has a width of about one Earth radius, yield a potential drop of several kV [Mozer, 1984; Hapgood and Lockwood, 1993]. The potential drop provided by the closed model is smaller than the observed potential drop of the order of 30 kV in quiet time. A qualitative picture is shown in Figure 2.

The open model assumes that some of the magnetospheric magnetic field lines are open, i.e., such field lines connect the Earth and the solar wind, and can pass through the magnetopause. A mechanism called "RECONNECTION" is responsible for producing open field lines. When two antiparallel magnetic field lines are close enough, reconnection can take place. Each original field line breaks into two parts, and each part of one field line connects to the nearby part of the other field line. The newly formed field lines are pulled away from the central reconnection region, which is called the "X-LINE", under the action of magnetic tension, since the new field lines are highly curved. The particles in the magnetic flux tube are thus accelerated by the reconnection mechanism.

When the IMF turns southward, reconnection occurs at the magnetopause. A qualitative picture is shown in Figure 3. At the dayside magnetopause, a newly arrived interplanetary magnetic field line reconnects to a magnetospheric closed field line, forming a pair of open field lines. One extends from the Earth to the north, while the other extends from the Earth to the south. The solar wind in the magnetosheath pulls the open field lines in an antisunward direction, resulting in antisunward plasma flow in the outer magnetosphere. In steady state, another reconnection region will exist in the nightside magnetotail in order to replenish the magnetic flux removed from the dayside. At the far-

Figure 3. A qualitative picture of the magnetospheric flow pattern in a noon-midnight meridian plane.

tail x-line, a pair of open field lines reconnects to form an interplanetary magnetic field line and a closed magnetospheric field line. Such a newly reconnected closed flux tube accelerates plasma loaded in it, forming a sunward plasma flow in the plasma sheet. This mechanism is estimated to be powerful enough to explain the observed potential drop in the polar cap.

C. The Plasma Sheet and Substorms

The plasma sheet is formed by closed magnetic field lines, and it contains a large fraction of the total particle energy in the magnetosphere. It is a highly dynamic region and has a close relation with the characteristic magnetospheric phenomenon called a "SUBSTORM". A substorm results in a sudden and explosive release of energy. When the IMF turns southward, reconnection takes place at the dayside magnetopause. The newly reconnected open field lines are pulled to the nightside and piled up in the tail lobe. The magnetotail field lines are strongly stretched, and a large amount of magnetic energy is stored in the magnetotail. At the onset of the "EXPANSION PHASE", which is sometimes related to a northward turning of the IMF, the plasma sheet suddenly becomes very thin. A "NEAR-EARTH X-LINE" is probably formed, according to a popular substorm scenario. Reconnection breaks the original long stretched closed field line into a short closed field line and a plasmoid. The plasmoid is ejected in the tailward direction. The plasma sheet expands again in the "RECOVERY PHASE".

Since the physical process never happens exactly the same way twice, the dynamics of it is still not clear. On the average, the flow in the plasma sheet is slow and earthward.

D. Pressure-Balance Inconsistency

In the magnetotail within $40 R_E$ of the Earth, the average earthward convection of plasma is slow with respect to both Alfvén and sound speeds, and the particle distribution

is nearly isotropic. In such a situation, the theory of adiabatic drift implies that $pV^{5/3}$ is approximately constant along a drift path [Wolf, 1983], where p is the thermal pressure of particles, and V is the volume of a unit magnetic flux tube. Based on the conventional assumption that plasma flows systematically earthward through the Earth's plasma sheet, one would naively expect the particle pressure p to vary with position in the plasma sheet in approximate proportion to $V^{-5/3}$. However, Figure 4 shows that there is a large systematic difference between the gradient of the observed average pressure and the gradient of $V^{-5/3}$, as estimated from the observation-based Tsyganenko [1987] model of the magnetospheric magnetic field. For instance, suppose that one estimates $pV^{5/3}$ from the average observed pressure and the Tsyganenko [1987] flux-tube volume at $x = -30 R_E$. Applying that value of $pV^{5/3}$ at $x = -14 R_E$ implies a pressure that is an order of magnitude greater than the average observed pressure. This theoretical problem [Erickson and Wolf, 1980] is usually called the “pressure-balance inconsistency” or “pressure crisis”.

E. The Prior Work on “Bubbles”

Pontius and Wolf [1990] (hereafter abbreviated as “PW90”) suggested that if “bubbles” of underpopulated flux tubes exist in the plasma sheet, they would help to resolve the pressure-balance inconsistency. Specifically, they pointed out that a bubble that had substantially smaller $pV^{5/3}$ than its neighbors would drift rapidly earthward through the plasma sheet, under the action of the interchange instability. If such underpopulated flux tubes existed in sufficient numbers, they might form the source for the inner plasma sheet, where $pV^{5/3}$ is apparently much smaller than in the outer plasma sheet. PW90 pointed out that gradient/curvature drift of hot ions into the bubbles would eventually cause them to dissolve into the surrounding medium. They predicted that the bubbles would have three characteristics near the neutral sheet: (i) rapid earthward flow; (ii) lower particle pressure than neighboring flux tubes; (iii) stronger magnetic fields than their neighbors. They also

Figure 4. Pressure profiles in the midnight meridian. Pressures deduced from various observations are shown. The higher solid curve was obtained assuming adiabatic compression in the *Tsyganenko* [1987] model, normalized to give the right pressure at $x = -30$. The lower solid curve shows that the observed pressures are roughly consistent with $pV^{2/3} = \text{constant}$. From *Spence* [1989].

made very rough quantitative estimates of other bubble characteristics as follows:

Velocity. Building on a scheme developed to describe flux tubes of elliptical cross section flowing outward in Jupiter's magnetosphere from the Io plasma torus [Pontius and Hill, 1989], PW90 used Vasyliunas' equation to estimate the earthward flow velocity of a bubble in the Earth's plasma sheet; in this formalism, inertial effects are neglected, and bubble velocity is limited by ionospheric conductance. For nominal parameter choices, this calculation indicated $v_x^{\text{bubble}} \sim 1100$ km/s, which is comparable to the fast-mode speed in the plasma sheet. Such a large velocity violates the assumption of quasi-static equilibrium on which the Vasyliunas equation is based. PW90 guessed that inertial effects would limit the bubble velocity to a value of the order of the fast-mode speed.

Radius. On the basis of the bubble velocity estimated above and calculated ion gradient/curvature-drift velocities, PW90 estimated that a circular bubble with radius much less than $1 R_E$ would be destroyed by differential gradient/curvature drift before reaching the inner plasma sheet. Since they pictured bubbles as also being considerably smaller than the tail, they guessed a bubble radius of the order of $1 R_E$. Dividing a bubble diameter of $2 R_E$ by a typical speed of 1000 km/s gave ~ 10 s for the time required for a bubble to pass a spacecraft.

Very shortly after the appearance of the Pontius-Wolf paper, Baumjohann *et al.* [1990] reported that the AMPTE/IRM spacecraft frequently observed brief bursts of rapid earthward flow, with about the speed and duration that were predicted. Furthermore, these high-speed-burst flux tubes were observed to have stronger B_z (and thus stronger equatorial magnetic field) than neighboring flux tubes. The paper by Baumjohann *et al.* [1990] would have been an immediate confirmation of the Pontius-Wolf hypothesis, except for the fact that the average pressure inside the high-speed burst was observed to be slightly higher than in the surrounding medium, opposite to the prediction. Angelopoulos *et al.* [1992] have presented a more detailed statistical analysis of the AMPTE/IRM observations

of the high-speed bursts. Results of their superposed epoch analysis are shown in Figure 5. Panels (d) and (e) show small peaks in the ion density and ion temperature at the center of the velocity peak.

We should remark that *Sergeev et al.* [1990] had earlier invoked low-density, fast-moving flux tubes to explain certain transient-injection events. In fact, many of the ideas proposed in this thesis have been presaged by V. A. Sergeev and collaborators, from a more observational viewpoint [*Sergeev et al.*, 1987, 1990, 1992; *Sergeev and Lennartsson*, 1988]. We should also remark that *Goertz and Baumjohann* [1991] called upon bubbles and blobs (regions of high $pV^{5/3}$) to aid in the interpretation of statistical features of AMPTE/IRM plasma data.

F. The Aim of the Present Work

Building on the work of PW90, the present work aims to develop the theory of bubbles more fully and quantitatively, with particular emphasis on the following two questions:

1. Can the high-speed flows observed from AMPTE/IRM still be regarded as bubbles even though the particle pressure at the center of the fast flow seems on average to be slightly higher than in the immediately surrounding medium?
2. How much of the earthward flow of the plasma sheet has to be in the form of bubbles in order for the bubble phenomenon to remove the pressure-balance inconsistency?

Before undertaking quantitative analysis, it is useful to form a qualitative picture of the life history of a bubble. Suppose that a bubble is somehow born in the distant tail (the "young bubble" in Figures 6a and 6b). The bubble has substantially lower particle pressure p than its neighbors and consequently stronger magnetic field (so that total pressures approximately balance inside and outside the bubble.) Because the westward gradient/curvature currents are weaker inside the bubble than outside, the bubble will charge up positive on the dawn side, negative on the dusk side (Figure 6b), and will feel a

Figure 5. Results of the superposed epoch analysis applied to plasma and magnetic field data around the local velocity peaks for fast ion flows observed in the central plasma sheet. The plasma and magnetic field data were time centered around each velocity peak ($t = 0$) and averaged over the data base from -4 to $+4$ min. The resulting traces are shown in 10-second resolution. From Angelopoulos *et al.* [1992].

Figure 6. Cartoons illustrating some life stages of a bubble. Diagram (a) shows the noon-midnight meridian plane; in this view, the decelerating bubble and mature bubble would look very similar, and only the mature bubble is shown. Diagrams (b) and (c) show “overhead views”, specifically the view of an observer located high above the north pole; the dawn side is toward the top, the dusk side to the bottom. J_{GC} , J_{in} , and $J_{||}$ represent gradient/curvature-drift, inertial, and Birkeland currents. Diagram (b) shows a young bubble, diagram (c) a decelerating bubble. The overhead view of a mature bubble would be the same as that for the decelerating bubble, but inertial current would be negligible. In all cases, the Sun is to the left.

stronger dawn-dusk electric field than its neighbors do. It will start to accelerate toward the Earth. At first, the equatorial part of the flux tube will accelerate rapidly earthward. The acceleration is provided by $\mathbf{J}_{in} \times \mathbf{B}$, where $\mathbf{J}_{in}$ is the westward inertial current across the bubble; initially, this almost compensates for the reduction in the westward gradient/curvature current. Since the bubble's equatorial speed is likely to approach the Alfvén speed [PW90], we expect that the portion of the flux tube near the ionosphere will not move much, so that the tube will become rounder and more dipolar than its neighbors as it speeds earthward. As the bubble's field line becomes rounder, the inertial current decreases, and more of the cross-tail current is diverted along the field line. As the bubble approaches the Earth, its $\rho V^{5/3}$ -value will eventually approach those of its equatorial neighbors, both because the $\rho V^{5/3}$ of the surrounding plasma sheet decreases earthward and because particles gradient/curvature drift into the bubble, increasing its $\rho V^{5/3}$. Thus the earthward acceleration and the associated inertial current will eventually reverse (Figure 6c). After the earthward equatorial motion has declined sufficiently, inertial effects will become unimportant; we refer to this state as the “mature bubble”. Its shape is shown in Figure 6a – rounder than its neighbors, and with its ionospheric footprint poleward of the footprints of its equatorial neighbors. After the equatorial motion has slowed, the field line's equatorward ionospheric motion will eventually catch up. In the final stage of the bubble's life (“dying bubble” in the Figure 6a), it becomes indistinguishable from its neighbors in the plasma sheet.

II. TRACING OF A BUBBLE'S MAGNETIC FIELD LINE

It will be very difficult to make a full quantitative theory of the motion of a bubble, because it is a thin, fast-moving feature surrounded by complicated plasma processes. However, the problem is simplified tremendously if we consider just a mature bubble whose equatorial motion has slowed and which is consequently close to being in quasi-static equilibrium. It should be noted that the high-speed bursts reported by *Baumjohann et al.* [1990] were observed almost entirely near the apogee of AMPTE/IRM, which suggests that the spacecraft was detecting bubbles that were decelerating, were nearly mature, and had almost completed their earthward motion.

We now proceed to construct an approximate quantitative model of how the shape of a bubble field line differs from the field lines of the surrounding medium – a crucial point that was not considered by PW90. We picture the bubble as an unusual flux tube embedded in a smooth plasma-sheet structure with known properties. The bubble is thus treated as being in force balance with the surrounding medium. Force balance in the GSM y -direction is thus assumed given by:

$$p_{\text{bubble}} + \frac{B_{\text{bubble}}^2}{2\mu_0} = p_{\text{medium}} + \frac{B_{\text{medium}}^2}{2\mu_0} \quad (1)$$

Since we are picturing a bubble near quasi-static equilibrium, we assume that its particle pressure is constant along the flux tube. We also neglect friction forces. For the condition of force balance in the GSM xz -plane, we require that the magnetic tension acting in the bubble's flux tube balances the other terms in the momentum equation, which means that the curvature vector of the bubble flux tube is given by:

$$\mathbf{K} = \frac{\mu_0}{B_{\text{bubble}}^2} \left[\nabla \left(p_{\text{bubble}} + \frac{B_{\text{bubble}}^2}{2\mu_0} \right) + \rho \frac{D\mathbf{v}}{Dt} \right]_{\perp} \quad (2)$$

where $\perp$ means perpendicular to the direction of the bubble magnetic field.

We carry out a model calculation of the shape of a bubble's field line, neglecting the inertial term in (2) for the sake of simplicity. We assume a specific model for the background configuration of magnetic field and plasma, and assume that the equatorial magnetic field in the bubble exceeds that in the surrounding medium by a given factor. We can calculate the shape of the bubble's flux tube by numerically walking up the field line. A *Fuchs-Voigt* [1979] 2d analytic model is used as the background field configuration. Results of a sample calculation are shown in Figure 7. Various Fuchs-Voigt field lines are shown: the numerical labels specify the geocentric distance of the equatorial crossing point of the field line. Two field lines are shown crossing the equatorial plane at $-19 R_E$ (chosen because it is near the apogee of the AMPTE/IRM spacecraft, where the probability of observing the high-speed bursts is maximum). One field line represents the Fuchs-Voigt model, but the other one indicates the result of integrating (1) and (2) up from the equatorial plane, assuming that $B_{\text{bubble}} = 1.4 B_{\text{medium}}$ at that plane (the B_z measured near the bubble's center is $\sim 40\%$ above the value measured 4 minutes before the bubble's center, according to Panel (a) of Figure 5). Note that, owing to its more dipolar shape, the bubble's field line passes medium field lines that cross the equatorial plane as far as $55 R_E$ from the Earth. Table 1 compares the bubble's pressure p , volume V , and $pV^{5/3}$ with the corresponding characteristics of the medium field lines.

Four points need to be made:

1. Although the bubble's particle pressure p is slightly less than that of its immediate neighbors in the equatorial plane, it exceeds that of its surroundings along nearly all of its

Figure 7. Computed shape of a mature bubble, compared with neighboring field lines. *Fuchs-Voigt* [1979] field lines with equatorial crossing points 19, 20, 25,...,40 are displayed, along with a hypothetical bubble field line that crosses the equator at 19. The k value of the Fuchs-Voigt model used is 1.57.

Table 1. Comparison of Bubble Properties with Neighboring Flux Tubes

	Equatorial crossing point (R_E)	p	V	$pV^{5/3}$
Bubble	19	1237.2	1.387	2135
Medium	19	1239.6	1.378	2115
Medium	20	1230.1	1.497	2410
Medium	25	1189.4	2.033	3880
Medium	30	1154.2	2.468	5202
Medium	35	1121.3	2.835	6367
Medium	40	1089.6	3.163	7425

length.

2. Although the bubble's $pV^{5/3}$ is very slightly larger than that of its neighbors right at the equatorial plane, it is substantially smaller than that of its neighbors along most of its length.

3. To estimate the relative impact of the inertial term in (2) on the equatorial curvature of the field line, we can write

$$\left| \frac{\rho v_x \frac{\partial v_x}{\partial x}}{\frac{\partial p_{TOT}}{\partial x}} \right| \sim 0.3 A \left(\frac{6 \text{ keV}}{kT_i} \right) \left(\frac{v_x}{400 \text{ km/s}} \right)^2 \frac{\Delta x_p}{\Delta x_v}$$

where p_{TOT} is the total pressure (particle plus magnetic), T_i is the ion temperature, and Δx_p and Δx_v are the scale lengths for variations in pressure and flow velocity, respectively. Thus inertial effects are likely to be quantitatively important, but not necessarily dominant, for flow velocities ~ 400 km/s.

4. In the high-speed bursts observed from the AMPTE/IRM near $x = -18 R_E$, Dv/Dt was probably tailward: the fact that the bursts were observed much more frequently near the spacecraft apogee than in the inner plasma sheet [Baumjohann *et al.*, 1990] strongly suggests that the plasma was decelerating as it moved earthward. In that case, the inertial term in (2) decreases the curvature of the bubble's field line, increasing the shape difference between the bubble and its neighbors. In other words, eastward inertial current across the bubble helps to generate the field-aligned currents that flow along the sides of the bubble (toward the ionosphere on the dawn side, away from the ionosphere on the dusk side). (See Figure 6c.) Thus consideration of the inertial term in (2) strengthens effects 1 and 2.

We therefore suggest that the $pV^{5/3}$ value of a high-speed burst is substantially smaller than that of its neighbors over most of its length, despite the fact that its pressure may be slightly larger than that of its neighbors over most of its length. This is exactly the

behavior that should be expected for a mature bubble, which is close to the end of its earthward motion in the equatorial plane. The basic reason why PW90 incorrectly predicted lower pressure inside the bubble than outside was that they did not consider the implications of the difference between the shapes of the bubble's field line and the neighboring field lines.

III. INTERPRETATION OF DETAILS OF FIGURE 5

Differential gradient/curvature drifts will tend to cause a bubble to “dissolve” into the surrounding medium. If we define a bubble as an object that drifts with an average ion, then energetic ions would drift into the bubble from the dawn side, and low-energy ions would drift in from the dusk side. The eastern and western sides of the bubble should have levels of $pV^{5/3}$, gradient/curvature-drift current, electric field, and earthward flow velocity v_x that are intermediate between the values at the center of the bubble and in the surrounding medium. Relative to the center of the bubble, the plasma on the east and west sides must be dragged in the tailward direction. The continuation of this process would transform a bubble that originally had almost any shape into an elongated form, as shown in Figure 8. (For the case of slow bubble motion, *Pontius* [1989] investigated this elongation process in considerable detail.) We therefore expect that $pV^{5/3}$ should increase monotonically from the head of the bubble to its tail, and the $pV^{5/3}$ value near the tailward end of the bubble should be close to that of the surrounding medium. The implication of this picture is that the peak of velocity is located at the head of the bubble. Therefore, the region of Figure 5 that is to the left of the peak represents the surrounding medium, while the region to the right of the peak is, in most cases, the domain of the bubble. The asymmetries displayed in panels (a) and (c) of Figure 5 support this picture.

The rapid motion of the bubble through a compressible medium should cause a small pressure increase in the medium just ahead of the bubble, and we might also expect some non-adiabatic heating; this may explain the gradual temperature rise to the left of the peak in Figure 5e. The superposed epoch analysis method may not separate the bubble from the compressed medium plasma immediately ahead of it. Since the medium just in front of the bubble is stationary relative to the head of a bubble, both have nearly the same maximum velocity and thus the same probability to be identified as the center of the velocity peak.

Figure 8. Sketch of the proposed equatorial cross-section of a bubble.

We would expect the tail of the bubble to be hotter than the undisturbed medium (upstream from the bubble), because it is the energetic ions that will gradient drift into the bubble most rapidly, and also because these ions may have undergone some nonadiabatic heating as they passed near the head of the bubble. This may explain why the ion temperature to the right of the peak in Panel (e) of Figure 5 (representing plasma in the tail of the bubble, which has been mixed with the hot ions from the surroundings) is higher than the ion temperature to the left of the peak, i.e., in the medium upstream of the bubble.

IV. NEW PICTURE OF PLASMA-SHEET TRANSPORT

In this section, we outline a new theoretical picture of how the plasma sheet works, based on the idea that bubbles play a central role in convection-associated earthward transport. We first present the picture in terms of cartoons of a fluid-mechanical analog, then in the form of very simplified mathematical models, which develop the idea that transport by high-speed bursts (i.e., bubbles) may resolve the pressure-balance inconsistency. The basic aim of the quantitative calculations will be to estimate how strong bubble-associated transport would have to be in order to eliminate the pressure-balance inconsistency.

A. Fluid-Mechanical Analog

To illustrate the essential physics of the plasma sheet as we now envisage it, we propose the fluid-mechanical analog shown in Figure 9. The analogy is based on the fundamental equivalence of the interchange instability in a confined plasma (which makes flux tubes of low $pV^{5/3}$ move toward regions of small flux-tube volume) and the gravitational Rayleigh-Taylor instability, which causes light fluid elements to rise above the denser fluid. The fluid-mechanical analog uses incompressible liquid ($\nabla \cdot \mathbf{v} = 0$), but different fluid elements have different densities. A unit volume in the bucket corresponds to a unit of magnetic flux in the magnetotail. Liquid density ρ corresponds to $pV^{5/3}$ in the plasma, since those are the key quantities that are conserved in the two cases as fluid elements move. The potential energy per unit volume in the liquid is ρgh and the potential energy per unit magnetic flux in the plasma is $(3/2)pV = (pV^{5/3}) (3/2) (V^{-2/3})$, which means that the liquid height h in the bucket corresponds to $V^{-2/3}$, aside from the scaling factor $(3/2g)$. The fact that average $pV^{5/3}$ decreases with decreasing geocentric distance (as shown in Figure 4), or that $pV^{5/3}$ tends to decrease with increasing $V^{-2/3}$, corresponds to

Figure 9. "Stratified fluid" model of the plasma sheet. More densely dotted regions represent dense liquid (analogous to high $\rho V^{5/3}$). The top of the container is analogous to the near-Earth magnetosphere, while the bottom corresponds to the distant tail. Diagram (a) is analogous to the simplest picture of sunward convection in the plasma sheet, with a uniform source in the distant tail and approximately uniform sunward flow (upward through the bucket). Diagram (b) is analogous to the model calculation discussed in Section IVB, which does not include gradient/curvature drift out the sides of the tail; the diagram corresponds to the case of $f > 0$, i.e., bubbles that are not empty. Diagram (c) represents the model calculation of Section IVC, with empty bubbles but with transport through the sides by gradient/curvature drift. Diagram (d) represents the case considered in Section IVD, with empty bubbles generated at various locations within the bucket; the bubble pipes replace dense fluid with zero-density fluid.

Figure 9.

the fact that average fluid density tends to decrease with increasing height in the bucket.

Liquid is fed in through the bottom of the bucket, corresponding to plasma being fed into the plasma sheet from a far-tail X-line and plasma-sheet boundary layer. Liquid spilling over the top of the bucket is analogous to escape of magnetospheric particles through the dayside magnetopause. Dense liquid, represented by densely dotted regions in diagrams (b) and (c), corresponds to flux tubes with high $pV^{5/3}$, while less-dense liquid, represented by sparsely dotted regions, corresponds to low $pV^{5/3}$. The cartoon shows several discrete density levels in diagrams (b) and (c), because of the limitations of the cartooning software. The actual physical analog would have a continuous range of densities.

Diagram (a) represents the simplest conceptual picture of convection in the plasma sheet, one that has been adopted in many computational models. Liquid with approximately uniform density (uniform $pV^{5/3}$) is fed in through the bottom of the bucket, and the same kind of liquid pours over the top. The bucket therefore has essentially uniform density ($pV^{5/3}$). The discrepancy between the observed pressure and the " $\propto V^{-5/3}$ " curve in Figure 4 indicates that Figure 9a does not correspond to the actual situation in the Earth's plasma sheet.

Diagrams (b)-(d) represent the new picture of the Earth's plasma sheet, designed for consistency with Figure 4. More specifically, they correspond to the three model calculations presented in Sections IVB-IVD. In all cases, the bucket contains liquid of different densities. The liquid naturally adopts a stratified structure, with higher densities (higher $pV^{5/3}$) on the bottom (far tail), and lower densities (lower $pV^{5/3}$) on the top. In both cases, bubbles constitute the primary mechanism by which fluid volume (magnetic flux) is transported upward (earthward). The overall upward motion of the liquid has two components: the bubbles, which occupy only a small fraction of the total volume, rise rapidly, and the background medium rises slowly. A typical liquid element of the

background medium has its density gradually reduced because of bubbles being dissolved into it; the element slowly rises in the bucket to maintain the level corresponding to that decreasing density. The system is assumed to be in steady state.

In diagram (b), the fluid injected through the bottom has a range of densities ($\rho V^{5/3}$). The lower-density liquid forms bubbles, which rise in the bucket. Once a bubble reaches a level in the bucket where the background density exceeds the bubble density by a fixed factor, the bubble is assumed to be absorbed into the surrounding liquid, lowering the average density of that medium.

Diagram (c) represents a variation on the same theme, with one complication eliminated and some new ones added. All bubbles are now assumed, for simplicity, to have zero density ($\rho V^{5/3} = 0$); bubble volumes decrease as they rise, because the bubbles are gradually dissolved into the medium. An additional complication is that liquid now leaks out through the left side of the bucket, in analogy to the gradient/curvature drift of ions through the dusk side of the magnetotail. Liquid is also now pumped slowly in through the right side of the bucket, representing the gradient/curvature drift of ions into the plasma sheet from the dawnside low-latitude boundary layer. The liquid pumped in from the right side has zero density ($\rho V^{5/3}=0$), an exaggeration of the fact that the LLBL has a much lower population of energetic ions than the plasma sheet.

Diagram (d) represents a case where bubbles are imagined to be spontaneously created at different locations in the fluid; an element of dense fluid is replaced by the same volume of zero-density fluid, which then rises.

The primary difference between the conventional picture (diagram (a)) and the proposed new picture (diagrams (b)-(d)) is that we now visualize the plasma sheet as a highly inhomogeneous and stratified fluid. A large fraction of the earthward transport is in the rapid earthward motion of bubbles.

B. Infinite-Width Magnetotail

In this section, we develop a simplified mathematical model of the type of bubble-dominated plasma-sheet transport that is analogous to Figure 9b, which includes bubbles of different densities moving upward (sunward), but does not consider loss out the sides of the bucket (tail). Bubbles are injected into the bucket through the bottom (far tail). Creation of low-density flux tubes in the far tail was suggested by *Sergeev et al.*[1990]. Let x be a coordinate that increases sunward in the plasma sheet, and suppose that bubbles at any given x have a spectrum of values of $K = pV^{5/3}$. Define a spectral function $F(K, x)$ such that $F(K, x) dK$ is the rate at which magnetic flux is convected past x per second in the form of bubbles that have $K < pV^{5/3} < K + dK$.

We neglect non-adiabatic heating, mainly because we do not know how to estimate it quantitatively. Thus we assume for simplicity that the K of a bubble is conserved until the bubble is absorbed into the medium. In a region where bubbles with $K = K_0$ are not being absorbed into the medium, we have $(\partial F(K_0, x)/\partial x)_{K_0} = 0$. Absorption of bubbles makes $\partial F/\partial x < 0$. In steady-state convection, we can write $\mathbf{E} = -\nabla\Phi$. The total potential drop across the tail at x is

$$\Phi_{\text{tot}} = \Phi_s(x) + \Phi_{\text{bubble}}(x) = \Phi_s(x) + \int F(K, x) dK \quad (3)$$

where $\Phi_s(x)$ is the potential drop across the flux tubes in the surrounding medium at x , $\Phi_{\text{bubble}}(x)$ is the potential drop in bubbles and Φ_{tot} is the total potential drop across the tail, which should be independent of x . In the fluid-mechanical analog of Figure 9, (3) corresponds to the condition

$$\int_{A(z)} v_z(x, y, z) dx dy = \text{independent of } z$$

where z is height in the bucket, and $A(z)$ is the cross-sectional area of the bucket at height z .

We can set up another equation by considering the following facts. The total pressure p is the sum of the partial pressures p_k of all species k , and the quantity $p_k V^{5/3}$ is conserved for each species. This implies that, for steady state,

$$(K\Phi)_{tot} = K_s(x) \Phi_s(x) + \int K F(K, x) dK \quad (4)$$

is independent of x , where $K_s(x)$ is the value of $pV^{5/3}$ in the surrounding medium. In the fluid-mechanical analog of Figure 9, (4) corresponds to the condition

$$\int_{A(z)} \langle \rho(x, y, z) v_z(x, y, z) \rangle dx dy = \text{independent of } z$$

where ρ is liquid density and the brackets indicate a time average.

On their earthward trek, the bubbles gradually absorb particles from the surrounding medium. Here we attempt to construct the simplest possible mathematical model of bubble-based transport that still includes bubbles with a range of K values. We approximate the medium-to-bubble particle transfer as occurring, for each bubble, at a single x -value, namely the x -value where $K_{bubble} = f K_s(x)$, where f is a constant coefficient between 0 and 1. That simple assumption reduces to

$$F(K, x) = \begin{cases} F(K, -40) & \text{if } K \leq fK_s(x) \\ 0 & \text{if } K > fK_s(x) \end{cases} \quad (5)$$

(The tailward boundary of the calculation is placed at $x = -40$.)

Then (3) reduces to

$$\Phi_{\text{tot}} = \Phi_s(x) + \int_0^{K_s} F(K, -40) dK \quad (6)$$

and (4) becomes

$$(K\Phi)_{\text{tot}} = K_s(x)\Phi_s(x) + \int_0^{K_s} K F(K, -40) dK \quad (7)$$

Equations (6) and (7) can be expressed in differential form:

$$0 = \frac{d\Phi_s(x)}{dx} + \frac{d(fK_s(x))}{dx} F(fK_s(x), -40) \quad (8)$$

$$0 = K_s(x) \frac{d\Phi_s(x)}{dx} + \Phi_s(x) \frac{dK_s(x)}{dx} + \frac{d(fK_s(x))}{dx} fK_s(x) F(fK_s(x), -40) \quad (9)$$

If we make a simple assumption that f is independent of x and take $K_s(x)$ from an observation-based magnetic field model, we can easily solve (8) and (9). The solution for the potential drop across the “surroundings” part of the medium, i.e., everything but the bubbles, is

$$\frac{\Phi_s(x)}{\Phi_s(-14)} = \left[\frac{K_s(-14)}{K_s(x)} \right]^{\frac{1}{1-f}} \quad (10)$$

We have chosen $x = -14$, near the inner edge of the plasma sheet, as a normalization point. We assume that the magnetic flux of bubbles is very small at $x \geq -14$ and thus identify $\Phi_s(-14)$ as the total potential drop across the tail, which can be estimated from the measurement of electric fields in the polar cap.

The ratio of potential drop in bubbles to the total potential drop can be expressed as

$$\frac{\Phi_{\text{bubble}}(x)}{\Phi_s(-14)} = 1 - \left[\frac{K_s(-14)}{K_s(x)} \right]^{\frac{1}{1-f}} \quad (11)$$

It is necessary at this point to discuss briefly the meaning of the limiting cases $f = 0$ and $f = 1$. If $f = 0$, then only the empty bubbles ($K = 0$) can cause any transport. If no empty bubbles are being produced, specifically if

$$\lim_{\varepsilon \rightarrow 0} \int_0^\varepsilon F(K, 40) dK = 0$$

then the bubbles have no effect. On the other hand, if the above integral has a non-zero limit, then the calculation makes sense in the limit $f \rightarrow 0$. The bubbles contribute to the transport of magnetic flux (i.e., to the cross-tail potential in (6)) but not to the transport of K , as represented by (7). This limiting case corresponds to empty bubbles being produced in the tail and absorbed at various x -values in the medium, as required to satisfy (6) and (7), or, alternatively, (8) and (9).

In the limiting case $f = 1$, the bubbles do not reduce the K -values of any medium flux tubes. If bubbles are produced with $K \geq K_0 = K_s(-14)$, then the number of flux tubes in the plasma sheet with $K \geq K_0$ would have to increase with time, which would violate the

assumption that the system is in steady state. The only solution for $f=1$ has the entire cross-tail potential drop in bubbles with $K = K_s(-14)$.

PW90 pointed out that the bubbles represent only a small fraction of the total volume of the plasma sheet at any given time, even though they might be responsible for most of the flux-tube transport. To estimate $K_s(x) = p_s V_s^{5/3}$, we therefore equate p_s , the pressure in the surrounding medium, to the observational-average pressure (from the data in Figure 4), and equate V_s , the flux-tube volume characteristic of the surrounding medium, to the observational-average flux-tube volume, calculated from the *Tsyganenko* [1987] model for $Kp \geq 5$.

The results of this calculation, performed without consideration of loss out the sides of the tail, are shown in Figure 10. Bubbles carry a smaller fraction of the cross-tail drop in the inner plasma sheet than in the distant plasma sheet, because bubbles are absorbed into the surrounding medium as they move earthward. For example, the figure indicates that bubbles could resolve the pressure-balance inconsistency if they could carry about 80% of the total cross-tail potential drop at $x = -40$, 40-50% of the total drop at $x = -20$, for the $f=0$ case.

C. Finite-Width Magnetotail

In the previous section, we worked out a simple model of bubble motion in the tail under the assumption that bubbles are the only mechanism responsible for the observed downtail gradient of $pV^{5/3}$. However, PW90 pointed out that, if a large fraction of the cross-tail potential drop is in bubbles (as indicated in Figure 10), then the average earthward drift speed of the surrounding flux tubes will be substantially reduced, which will enhance the effect of gradient/curvature drift out the sides of the tail, a process that was investigated in detail by *Kivelson and Spence* [1988]. This effect has been demonstrated observationally by *Angelopoulos* [1993] and *Angelopoulos et al.* [1993], who found that

Figure 10. Ratio of $\Phi_{\text{bubble}}(x)$, the potential drop in bubbles, to $\Phi_{\text{tot}}(x)$, the total potential drop across the geomagnetotail. The width of the tail is assumed infinite.

average ion flow in the plasma sheet near local midnight is predominantly in the $+y$ -direction, if the average excludes bursty bulk flows. We therefore revise the bookkeeping scheme of the previous section, so that we can take bubbles and gradient/curvature drift simultaneously into account. This calculation is analogous to Figure 9c.

Consider a particle drifting earthward from the dawn side of the magnetotail at $-60 R_E$. Its trajectory is expressed by $y_k(x)$, where k represents the species of the particle. The equation for $y_k(x)$ is

$$\frac{dy_k(x)}{dx} = \frac{v_{GC,k}(x)}{v_{E \times B}(x)} \quad (12)$$

where $v_{GC,k}(x)$ is the gradient/curvature drift speed of the particle and $v_{E \times B}(x)$ is its $\mathbf{E} \times \mathbf{B}$ drift speed. The velocity $v_{GC,k}(x)$ may be expressed as

$$v_{GC,k}(x) = \frac{\lambda_k}{q_k B_e(x)} \frac{d(V(x)^{-2/3})}{dx} \quad (13)$$

where $V(x)$ is the volume of a unit magnetic flux tube, q_k is the charge of the species k , $B_e(x)$ is the magnitude of magnetic field in the equatorial plane, and λ_k is the energy invariant for an isotropic distribution of species k [Wolf, 1983]. Particle thermal energy $E_k(x)$, flux-tube volume $V(x)$, and energy invariant λ_k are related by

$$E_k(x) = \lambda_k V(x)^{-2/3} \quad (14)$$

The velocity $v_{E \times B}(x)$ may be expressed as

$$v_{E \times B}(x) = \frac{\Phi_s(x)}{W B_e(x)} \quad (15)$$

where W is the width of the magnetotail, which is assumed independent of x , and $\Phi_s(x)$ is the potential drop across the plasma medium. Here we have assumed that the electric field in the tail is directed from dawn to dusk. In reality, coupling to the ionosphere will probably produce a significant earthward component [Erickson *et al.*, 1991], but we neglect that effect for the sake of simplicity. Substituting (13) and (15) into (12), we have

$$\frac{dy_k(x)}{dx} = \frac{\lambda_k W}{q_k \Phi_s(x)} \frac{d(V(x)^{-2/3})}{dx} \quad (16)$$

The dilution of plasma by bubbles implies an equation analogous to equation (4), i.e.,

$$\eta_k(x) \Phi_s(x) = \eta_k(-60) \Phi_s(-60) \quad (17)$$

where $\eta_k(x)$ is the number of particles of type k per unit magnetic flux in the background medium, for $y > y_k(x)$. We assume for simplicity in this calculation that the bubbles are empty. We also assume that there are no particles of species k for $y < y_k(x)$, which means that we neglect the low-latitude boundary layer as a source of plasma-sheet particles. A quantitative assessment of the effect of LLBL particles on plasma-sheet pressure and density has been given by Spence and Kivelson [1993]. (Equation (17) is equivalent to equation (9) of Pontius and Wolf [1990].) The y -averaged $pV^{5/3}$ value of the surrounding medium is thus given by

$$p V^{5/3} = \frac{2}{3} \sum_{k=1}^m \eta_k(x) \lambda_k \left(1 - \frac{y_k(x)}{W} \right) \quad (18)$$

where the summation is over all species.

The particles are approximated as a Maxwellian distribution at -60 , with the ion temperature there set equal to 2.5 keV [Rich, 1973]. The particle number density may be represented as

$$n_k(-60) = D \sqrt{E_k} \Delta E_k \exp(-E_k/kT_i) \quad (19)$$

where D is a normalization constant and T_i is the ion temperature at $x = -60$. With some complicated algebra, we can combine (14), (16), (17), (18), (19) into the following set of $m+1$ equations:

$$\frac{dy_k(x)}{dx} = \frac{E_k W}{q_k \Phi_s(-60)} \frac{p(x)}{p(-60)} \frac{V(x)^{5/3}}{V(-60)} \frac{\left[\sum_{k=1}^m E_k^{3/2} \Delta E_k \exp(-E_k/kT_i) \right]}{\left[\sum_{k=1}^m E_k^{3/2} \Delta E_k \left(1 - \frac{y_k(x)}{W} \right) \exp(-E_k/kT_i) \right]} \frac{d(V(x)^{-2/3})}{dx} \quad (20)$$

for $k=1$ to m , and

$$\Phi_s(x) = \Phi_s(-60) \frac{p(-60)}{p(x)} \frac{V(-60)^{5/3}}{V(x)^{5/3}} \frac{\left[\sum_{k=1}^m E_k^{3/2} \Delta E_k \left(1 - \frac{y_k(x)}{W} \right) \exp(-E_k/kT_i) \right]}{\left[\sum_{k=1}^m E_k^{3/2} \Delta E_k \exp(-E_k/kT_i) \right]} \quad (21)$$

In these expressions, $E_k \equiv E_k(-60)$, and ΔE_k is the width of the energy band for species k , at $x = -60$.

Equations (20) and (21) can be numerically integrated by walking the solution earthward from $x = -60$, for a given value of the potential drop $\Phi_s(-14)$. The pressure $p(x)$ is estimated from the data of Figure 4, and the volume $V(x)$ is calculated from the *Tsyganenko* [1987] model, for local midnight. The value of Kp used for the *Tsyganenko* model is chosen to be consistent with the value of the total cross-tail potential drop, which is identified as the value $\Phi_s(-14)$ obtained from the numerical integration. In our numerical calculations, the number of species m is set to 100.

Numerical results are shown in Figure 11. Note that for many conditions, the pressure-balance inconsistency can be removed if empty bubbles carry a moderate fraction of the total cross-tail potential drop, at least within this simplified model. For smaller cross-tail potentials, the bubbles have to carry a smaller percentage of the total drop. For a 50-kV drop, for example, bubbles carry about 56% of the total drop at $x = -40$, only about 20% at $x = -20$.

We can speculate as to a possible connection to substorms. Suppose that the system is in steady state with $\Phi_{\text{tot}} = 50$ kV, with $0.56 \times 50 = 28$ kV in the form of bubbles (at $x = -40$). Suppose further that the IMF suddenly turns southward, giving a total potential drop of 180 kV. Figure 11 indicates that, to maintain a steady state, the production of bubbles would have to increase to $0.73 \times 180 = 131$ kV. Suppose that the actual bubble production increases more modestly. Then high- $pV^{5/3}$ flux tubes will gradually pile up in the tail. From the work of *Erickson* [1992], we know that would cause an increase in the tail-lobe field and severe field-line stretching in the inner plasma sheet, which is similar to what happens in the growth phase of a substorm.

For sufficiently low values of the cross-tail potential, the computed $\Phi_{\text{bubble}}(x)$ reaches a maximum at $x < -14$, then decreases earthward. This means that, for sufficiently small

Figure 11. Ratio of $\Phi_{\text{bubble}}(x)$, the potential drop in bubbles, to $\Phi_{\text{tot}}(x)$, the total potential drop across the geomagnetotail, for the case of a finite-width tail. Ions are lost by gradient/curvature drift through the dusk magnetopause. The curves are labeled by the value of Φ_{tot} , the total cross-tail potential drop. The curve labeled " ∞ " represents the limit where gradient/curvature drift is unimportant (same as $f=0$ curve in Figure 10).

cross-tail potential drops, gradient/curvature drift is more than sufficient, by itself, to eliminate the pressure-balance inconsistency in the inner plasma sheet, at least within our simplifying assumptions. This is qualitatively consistent with the conclusion of *Kivelson and Spence* [1988], which is not surprising, since the simplifying assumptions of our calculations are very similar to theirs, except for our inclusion of the bubble effect.

D. Bubbles Created in the Plasma Sheet

Now consider the case where bubbles are somehow created within the modeled region of the plasma sheet. For the sake of simplicity, neglect drift through the dawn and dusk magnetopause. Also assume for simplicity that the bubbles are empty, so that the particle transport is all in the surrounding medium. The creation of the bubble replaces flux tubes that had specific entropy $K_s(x)$ with flux tubes with specific entropy zero, and we can thus write

$$\frac{d(K\Phi_{\text{tot}})}{dx} = \frac{d(K_s(x)\Phi_s(x))}{dx} = -h(x)K_s(x) \quad (22)$$

where $h(x)$ is the bubble creation rate (magnetic flux per unit time per unit length in x).

Using the fact that $\Phi_{\text{bubble}}(x) + \Phi_s(x) = \text{constant}$, we can rewrite (22) to give

$$\frac{d\Phi_{\text{bubble}}}{dx} = h(x) + \Phi_s(x) \frac{d[\ln(K_s(x))]}{dx} \quad (23)$$

The first term on the right of (23) is positive, but, because K_s increases tailward, the second term on the right is negative. If the first term dominates (strong bubble generation), then Φ_{bubble} will increase earthward. However, if the second term dominates (weak bubble generation), then Φ_{bubble} will decrease earthward, as occurred in Figures 10 and 11.

If one is worried about the large fraction of total convection required at $x = -40$ in Figures 10 and 11, for large f and large Φ_{tot} , the problem can clearly be reduced by assuming significant bubble generation at $x > -40$.

V. SUMMARY AND DISCUSSION

A. Summary of Results

By using a *Fuchs-Voigt* [1979] two-dimensional force-balanced magnetic field model, we have proved that, if there exists a magnetic flux tube in the plasma sheet that has rounder shape and stronger equatorial magnetic field than its neighbors, then its $pV^{5/3}$ -value tends to be considerably smaller than that of its neighbors along most of its length, even though its pressure may be higher. Such a magnetic flux tube, which we call a “bubble”, is indeed depleted of plasma.

The intersection of a typical bubble with the equatorial plane would have a long antisunward-pointing tail, with its distant part almost indistinguishable from the surrounding medium. The bubble's head, which is most depleted of plasma, travels earthward at a speed that is much higher than that of the surrounding plasma. The head of a bubble should slightly increase the pressure in the medium in front of it, and the heated ions would partly penetrate the bubble as they pass by, resulting in drag. This process is powerful enough to cause the bubble to dissolve into the surrounding medium when it gets sufficiently close to the Earth.

Overall, the characteristics of the observed high-speed flows [*Baumjohann et al.*, 1990; *Angelopoulos et al.*, 1992] seem very close to what should be expected of a “mature bubble” that is close to the end of its rapid sunward motion.

It is likely that bubbles play a major role in resolving the pressure-balance inconsistency. Particle loss by drift out of the sides of the magnetotail may explain the observed pressure in the inner plasma sheet in quiet times [*Kivelson and Spence*, 1988], but for intermediate and active times bubbles represent a strong candidate-mechanism for resolving the pressure dilemma.

We have sought to make rough estimates of what fraction of the cross-tail potential drop would have to be in bubbles, in order for the pressure-balance inconsistency to be resolved. The basic conclusions are:

1. Assuming empty bubbles and average conditions ($\Phi_{\text{tot}} = 50$ kV), and assuming that bubbles form only in the distant tail, then $\Phi_{\text{bubble}}/\Phi_{\text{tot}}$ rises from about 20% at $x = -20$ to about 56% at $x = -40$.
2. The required value of $\Phi_{\text{bubble}}/\Phi_{\text{tot}}$ increases if the bubbles are not empty and if the total potential drop exceeds 50 kV.
3. If all bubbles are generated in the distant tail, then the ratio $\Phi_{\text{bubble}}/\Phi_{\text{tot}}$ increases with increasing distance from the Earth. However, $\Phi_{\text{bubble}}/\Phi_{\text{tot}}$ may decrease tailward through a region of the plasma sheet where bubbles are being generated.

B. Possible Mechanisms for Forming Bubbles

We now turn to some speculation concerning how bubbles of low- $pV^{5/3}$ plasma might be formed. Most of the mechanisms that we can think of involve magnetic reconnection.

1. Variations in $pV^{5/3}$ among flux tubes formed at a distant X-line. ISEE-3 data indicate that, on the average, the far-tail X-line lies considerably further from the Earth near the flanks of the tail than near local midnight [Slavin *et al.*, 1985]. Since flux-tube volume tends to increase with flux-tube length, we would expect that new closed flux tubes formed near the flanks of the magnetosphere would have larger $pV^{5/3}$ -values than tubes formed near local midnight. In steady state, this situation seems likely to create an earthward stream of low- $pV^{5/3}$ tubes, centered somewhere near local midnight. It is probably significant that Baumjohann *et al.* [1990] found highest occurrence of high-speed bursts near local midnight. Theoretically, it is not clear that this midnight-centered stream should be steady. For one thing, reconnection at the far-tail X-line may be patchy; after all, flux-transfer events are usually interpreted in terms of patchy reconnection at the dayside

magnetopause. Furthermore, even if the low- $pV^{5/3}$ flux tubes are formed in a steady fashion, a Kelvin-Helmholtz or other instability may act to break up a fast-moving sunward stream into discrete bubbles. On the observational side, steady earthward-streaming motion has, in fact, been observed several times in the inner plasma sheet [Sergeev and Lennartsson, 1988], and we suspect that this observed phenomenon may have the same basic physical origin as the high-speed bursts observed by Baumjohann *et al.* [1990].

2. Secondary reconnection within the closed-field-line plasma sheet. Suppose that reconnection occurs on a long, stretched plasma-sheet closed field line, creating a shorter closed field line and a plasmoid. Since the plasma that was originally on the flux tube is now split between the newly closed field line and the plasmoid, the new short closed tube has lower $pV^{5/3}$ than the original long one. Such a reconnection process automatically creates a bubble, which will move toward the Earth. This type of bubble creation is represented in Figure 9d, with bubble pipes representing patches of reconnection.

In their original paper on high-speed bursts, Baumjohann *et al.* [1990] suggested reconnection further out in the plasma sheet as a probable mechanism for creating the bursts. We should emphasize that the bubble mechanism originally suggested by PW90 and the reconnection mechanism suggested by Baumjohann *et al.* [1990] are not competing explanations of the high-speed-burst phenomenon. They are basically two ways of looking at the same process. In principle, the bubble mechanism could be a little bit more general, in the sense that bubbles may be created by mechanisms other than reconnection; an example might be patchiness in a closed-field-line low-latitude boundary layer. However, a burst of reconnection in a region of the closed-field-line plasma sheet should always create a bubble.

In simple calculations of tail reconnection, plasma near the equatorial plane is accelerated away from the X-line by magnetic tension, at a speed that is of the order of the Alfvén speed. However, this rapid outflow slows as it approaches the Earth, being

strongly affected by increased plasma pressure and magnetic field near the Earth, which are hard to represent accurately in detailed simulations of the reconnection region. Far to the earthward side of the X-line, it is better to visualize newly reconnected flux tubes as bubbles moving in a medium that is otherwise slow-moving and close to equilibrium. The magnetic-buoyancy picture provides a way to visualize how low- $pV^{5/3}$ flux tubes produced by a patch of reconnection move as they approach the Earth.

C. Concluding Comments

This work represents a step toward a new theoretical picture of the Earth's plasma sheet, a picture in which underpopulated flux tubes form high-speed bursts that play a central role in sunward convection in the plasma sheet. More high-time-resolution measurements are needed from the plasma sheet beyond $20 R_E$ to test the basic theoretical picture, and to identify the mechanism that produces the bubbles.

REFERENCES

- Angelopoulos, V., Transport Phenomena in the Earth's Plasma Sheet, Ph. D. thesis, UCLA, Los Angeles, 1993.
- Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pellat, R. J. Walker, H. Lühr, and G. Paschmann, Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res.*, 97, 4027, 1992.
- Angelopoulos, V., C. F. Kennel, F. V. Coroniti, R. Pellat, H. E. Spence, M. G. Kivelson, R. J. Walker, W. Baumjohann, W. C. Feldman, J. T. Gosling and C. T. Russell, Characteristics of ion flow in the quiet state of the inner plasma sheet, to be published in *Geophys. Res. Lett.*, 1993.
- Axford, W. I., and C. O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, *Can. J. Phys.* 39, 1433, 1961.
- Baumjohann, W., G. Paschmann, and H. Lühr, Characteristics of high-speed ion flows in the plasma sheet, *J. Geophys. Res.*, 95, 3801, 1990.
- Dungey, J. W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, 6, 47, 1961.
- Erickson, G. M., and R. A. Wolf, Is steady convection possible in the earth's magnetotail?, *Geophys. Res. Lett.*, 7, 897, 1980.
- Erickson, G. M., R. W. Spiro, and R. A. Wolf, The physics of the Harang discontinuity, *J. Geophys. Res.*, 96, 1633, 1991.
- Fuchs, K., and G. -H. Voigt, Self-consistent theory of a magnetospheric B-field model, *Geophys. Monograph.*, 21, 86, 1979.
- Goertz, C. K., and W. Baumjohann, On the thermodynamics of the plasma sheet, *J. Geophys. Res.*, 96, 20991, 1991.
- Hapgood, M., and M. Lockwood, On the voltage and distance across the low latitude boundary layer, *Geophys. Res. Lett.*, 20, 145, 1993.

- Kivelson, M. G., and H. Spence, On the possibility of quasi-static convection in the quiet magnetotail, *Geophys. Res. Lett.*, 15, 1541, 1988.
- Mozer, F. S., Electric field evidence for viscous interaction at the magnetopause, *Geophys. Res. Lett.*, 11, 981, 1984.
- Pontius, D. H., Jr., Transient flux tubes in the terrestrial magnetosphere, paper presented at The Sixth Scientific Assembly of the International Association of Geomagnetism and Aeronomy, Exeter, United Kingdom, 24 July-4 August, 1989.
- Pontius, D. H., Jr., and T. W. Hill, Rotation driven plasma transport: The coupling of macroscopic motion and microdiffusion, *J. Geophys. Res.*, 94, 15041-15053, 1989.
- Pontius, D. H., Jr., and R. A. Wolf, Transient flux tubes in the terrestrial magnetosphere, *Geophys. Res. Lett.*, 17, 49, 1990.
- Rich, F. J., Plasma in the geomagnetic tail observed by the charged particle lunar environment experiment, *Ph. D. thesis*, Rice University, Houston, Texas, 1973.
- Sergeev, V. A., V. S. Semenov, and M. V. Sidneva, Impulsive reconnection in the magnetotail during substorm expansion, *Planet. Space Sci.*, 35, 1199-1212, 1987.
- Sergeev, V. A. and W. Lennartsson, Plasma sheet at $X \approx -20 R_E$ during steady magnetospheric convection, *Planet. Space Sci.*, 36, 353, 1988.
- Sergeev, V. A., O. A. Aulamo, R. J. Pellinen, M. K. Vallinkoski, T. Bösinger, C. A. Cattell, R. E. Elphic, and D. J. Williams, Non-substorm transient injection events in the ionosphere and magnetosphere, *Planet. Space Sci.*, 38, 231-239, 1990.
- Sergeev, V. A., R. C. Elphic, F. S. Mozer, A. Saint-Marc, and J. A. Sauvaud, A two-satellite study of nightside flux transfer events in the plasma sheet, *Planet. Space Sci.*, 40, 1551-1572, 1992.
- Slavin, J. A., E. J. Smith, D. G. Sibeck, D. N. Baker, R. D. Zwickl, and S. -I. Akasofu, An ISEE 3 study of average and substorm conditions in the distant magnetotail, *J. Geophys. Res.*, 90, 10875, 1985.

- Spence, H. E., On the large-scale distribution of magnetospheric currents and thermal plasma: Results from magnetic field models and observations, *Ph. D. thesis*, UCLA, 1989.
- Spence, H. E., and M. G. Kivelson, Contributions of the low-latitude boundary layer to the finite width magnetotail convection model, subm. to *J. Geophys. Res.*, 1993.
- Tsyganenko, N. A., Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels, *Planet. Space Sci.*, 35, 11, 1347, 1987.
- Wolf, R. A., The quasi-static (slow-flow) region of the magnetosphere, in R. L. Carovillano and J. M. Forbes (Eds.), *Solar Terrestrial Physics: Principles and Theoretical Foundations*, D. Reidel Publ. Co., Hingham, MA, pp. 303-368, 1983.