THE ROLE OF PLASMA INTERCHANGE MOTION FOR THE FORMATION OF A PLASMAPAUSE*

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Abstract—McIlwain's electric and magnetic field distributions (E3H and M2) have been used to calculate the drift path of plasma density irregularities, taking into account plasma interchange motion driven by the gravitational and inertial forces acting on the whole mass of the plasma elements.

It has been shown that there is a region in the magnetosphere which is unstable with respect to the interchange motion of the cold plasma element. Any plasma hole in the background density drifts ultimately toward an asymptotic trajectory. Along this trajectory the inward gravitational force is balanced by the outward inertial force averaged over one revolution around the Earth. This asymptotic trajectory, along which all plasma holes ultimately accumulate, is identified with the equatorial plasmapause. The maximum velocity for the interchange motion is proportional to the integrated Pedersen conductivity. Plasma detachment is shown to occur preferentially in the post-midnight sector.

INTRODUCTION

The plasmapause is the relatively sharp boundary where the density of cold plasma of ionospheric origin decreases rather abruptly from 100-300 electrons and ions cc^{-1} to a value of 1-5 particles cc^{-1} . The plasmapause is a toroidal surface within which very low energy particles trapped in the magnetic and gravitational field are confined and corotate with the angular speed of the Earth. The radial distance of the plasmapause surface in the equatorial plane ranges from L = 3 to 8 depending on geomagnetic conditions, local time (L.T.) and universal time (U.T.). Figure 1 shows, for instance, the electron density in the plasmasphere vs McIIwain's parameter (L) along an inbound trajectory of OGO 5. Depressions in the plasmaspheric density as shown in Fig. 1 are often observed. Enhancements of the plasmaspheric density also seen in Fig. 1 have been called detached plasma elements or plasma tails by Chappell (1974), Chen and Wolf (1972), Grebowsky (1971).

A numerical program to calculate the motion of such plasma irregularities in the magnetosphere has been developed by the present authors. The purpose of this paper is to present new results concerning the formation of the plasmapause as deduced from this theoretical model.

VELOCITY OF PLASMA ELEMENTS

The drift velocity of plasma elements is a superposition of a large scale "convection velocity" of the background magnetospheric plasma, and an "interchange velocity" in the direction of the external force acting on the total mass of these density irregularities.

1. The large scale convection velocity (v)

This is determined by the distribution of the magnetic field (\mathbf{B}) and of the electric field (\mathbf{E}) in the magnetosphere:

$$\mathbf{v} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \,. \tag{1}$$

The dipole magnetic field and the uniform dawndusk electric fields have often been adopted. More realistic magnetic and electric field distributions have been deduced from various types of observations. McIlwain's E3H and M2 electric field and magnetic field models are examples of such empirical field distributions which were deduced from ATS 5 particle observations and magnetic field measurements (McIlwain, 1972, 1974).

Figure 2 shows the equatorial convection velocity using the E3H and M2 models of McIlwain. The vectors shown in Fig. 2 give the $\mathbf{E} \times \mathbf{B}/B^2$ velocity which is also the drift velocity for very low energy electrons and ions in the equatorial plan. Note that in the inner magnetosphere, for L < 4, cold plasma corotates with the angular velocity of the Earth. But in the post-midnight sector, for L > 5, the convection velocity is much larger than corotation in the eastward direction and the acceleration has the largest values.

Figure 3 shows the drift path of zero energy test particles in the equatorial plane. These trajectories

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FIG. 1. H^+ ion density measured by OGO 5 as a function of equatorial distance (L), and local time (L.T.) (from NSSDC).

Note the plasma density irregularities and large depressions in the H⁺ distribution.

are closed loops parallel to electric equipotential surfaces for the E3H field. Different symbols have been used to indicate the positions of the particles at every successive hour of U.T. after their release in the noon meridian plane at t = 0. The size of the symbols is proportional to the size of gyro-circle of the drifting particles.

2. The interchange velocity

In addition to their electric drift velocity, given by equation (1), zero energy electrons and protons also have small drifts due to the external forces (**F**) acting on their mass (m): e.g. the gravitational force (mg), and the inertial force ($m d\mathbf{v}/dt$). As illustrated in Fig. 4, these drifts are perpendicular to **F** and they are in opposite directions for positively and negatively charged particles.

Because of the small mass of a proton, the drift due to gravitational or centrifugal forces is more than a million times smaller than the electric drift velocity. Nevertheless, owing to this small gravitational drift, the electrons and ions move in opposite directions away from each other. If the plasma density distribution were uniform, no net charge separation would then result from the gravitational drifts. However, plasma density irregularities, like those shown in Fig. 1, are present in the magnetosphere. Therefore, net polarization charges of opposite signs are accumulating on the eastward and westward sides of a plasma element, as illustrated in Fig. 4. These polarization charges modify the electric field inside and in the vicinity of the plasma cloud. As a consequence, the electric drift velocity inside the plasma element is not exactly equal to the large scale convection velocity outside



FIG. 2. EQUATORIAL ELECTRIC DRIFT VELOCITY CALCULATED FOR MCILWAIN'S ELECTRIC AND MAGNETIC FIELD MODELS E3H AND M2.

Note the large convection velocity in the post-midnight sector for L > 4.



FIG. 3. EQUATORIAL DRIFT PATHS OF ZERO ENERGY TEST PARTICLES IN MCILWAIN'S ELECTRIC AND MAGNETIC FIELD DISTRIBUTIONS.

Also the drift paths of plasma elements when the plasma interchange velocity is vanishingly small, i.e. when Σ_p , the integrated Pedersen conductivity, is assumed to be infinitely large. The 5 different symbols used to mark the positions along the trajectories correspond to the beginning of each new hour of U.T. The size of the successive symbols is proportional to the equatorial cross-section of the drifting plasma clouds. The plasma elements are released at t = 00 U.T. along the local noon equatorial radius, at R = 2, 3, 4, 5, 6, 7, 8 and 9 R_E . Note that these trajectories are parallel to the equipotential surfaces of the E3H electric field, only when $\Sigma_p = \infty$.

the plasma irregularity. This is equivalent to saying that the additional polarization electric field, produced by the plasma element itself, gives an additional electric drift velocity which, by definition, is the interchange velocity of the plasma irregularity. This interchange velocity is in the direction of the external force acting on the plasma element: i.e. the gravitational force, and the centrifugal or inertial force acting on the total mass of the plasma irregularity. The interchange velocity tends to move the mass element along a trajectory slightly different from that shown in Fig. 3. The tendency is to move the mass element toward a region of lower potential energy (see also Lemaire, 1975).

The maximum interchange velocity (**u**) is proportional to the excess mass (ΔnmV) of the plasma element, and inversely proportional to the integrated Pedersen conductivity (Σ_p) of the ionosphere where the potential energy lost by the falling element is dissipated by Joule heating and viscous drag in the *E*-region of the ionosphere (Walbridge, 1967; Cole, 1971).

$$\mathbf{u} = \frac{8L^3 \Delta nmV \left(\mathbf{g} + \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}r}\right)}{S_I B_I^2 \Sigma_p} \tag{2}$$

where *m* is the mass of the ions; *L* is McIlwain's parameter of the magnetic field line along which the centre of mass of the element is located; B_I is the magnetic field intensity at *E*-region altitudes where this magnetic field line dips into the ionosphere; S_I is the ionospheric cross-section of the magnetic flux tube within which the plasma element is confined; the actual volume *V* of the plasma irregularity is assumed to be a fraction (α) of the total volume of a dipole magnetic flux tube (i.e. $V = \alpha V_{\text{DIP}}$). Both S_I and V_{DIP} are functions of *L*



FIG. 4. THE SMALL GRAVITATIONAL DRIFTS OF ELECTRONS AND PROTONS PRODUCE AN ACCUMULATION OF NEGATIVE AND POSITIVE CHARGES, RESPECTIVELY ON THE WESTWARD AND EASTWARD SIDES OF A PLASMA ELEMENT.

These electric charges produce a polarization electric field inside and in the vicinity of the plasma density enhancement. This electric field must be added to the external electric field. Therefore, in addition to its convection velocity due to the external *E*-field, the plasma inside the element is accelerated in the direction of the gravitational force acting on the whole mass of the plasma irregularity. The resulting interchange velocity has however a maximum value which is inversely proportional to the integrated Pedersen conductivity in the ionosphere along the magnetic field lines passing through the plasma element. The maximum interchange velocity is also proportional to the difference of mass density between the plasma inside and outside of the element.

which have been calculated in Lemaire (1976). For plasma clouds concentrated near the equatorial plane, between -25° and $+25^{\circ}$ of latitude, α is approx. equal to 0.5; it is this value that has been adopted in the following numerical calculations; Δn , the difference between the equatorial density inside and outside of the plasma element, can be either positive (in the case of a plasma density enhancement) or negative. The latter case corresponds to a plasma hole with an internal density smaller than the ambient background density. Note that in the following calculations we have assumed that the background density distribution can be described by the classical L^{-4} variation, with a reference level density of 500 cm⁻³ at L = 4.

When the integrated Pedersen conductivity is assumed to be infinitely large, the electric field inside the element is equal to the electric field outside the element, and the maximum interchange velocity is then zero. In this ideal case the drift paths of plasma density irregularities are closed loops like the trajectories of zero energy test particles shown in Fig. 3. (The size of the symbols along the trajectories is proportional to 1/B: i.e. proportional to the cross-section of the drifting plasma element; indeed, the total magnetic flux is conserved during the motion around the Earth.)

DRIFT PATHS OF COLD PLASMA ELEMENTS

Let us now consider another case when the integrated Pedersen conductivity is not infinitely large, but where it is reduced to a realistic value. The empirical model of Gurevich *et al.* (1976) was adopted to describe the latitude and L.T. distribution of the integrated Pedersen conductivity. Now the interchange velocity, which is inversely proportional to the Pedersen conductivity, is no longer equal to zero. In the post-midnight sector, where the ionospheric conductivity is minimum and where the centrifugal acceleration is maximum (see Fig. 2), the interchange velocity is also maximum.

Inside the plasmasphere the centrifugal force acting on the total mass of the plasma element is smaller than the gravitational force. As a consequence of interchange motion, an equatorial plasma element with an enhanced density slowly slips toward the Earth. Indeed, in this case the net force on the total mass, and consequently the interchange velocity, are both directed inwards.

The solid line in Fig. 5 shows the inward spiraling drift path of such an excess mass. As before, the symbols $(+, \times ...)$ indicate the position of the plasma element at every hour U.T. after it has been released in the local noon meridian plane at an equatorial distance of $4R_E$. The change in size of the 5 symbols used denote the change in the equatorial cross section of plasma elements along their trajectories.

Dayside flux tube refilling and nightside downward ionization flow can change this trajectory. Although, this effect has been incorporated in our computer program, it will not be discussed in the present report. Therefore, we limit the present study to the simpler cases for which the total mass of a plasma element is conserved.

Furthermore, gradient-B and curvature drifts for non-zero energy plasma particles also contribute to polarize plasma elements when their temperature is not vanishingly small (Richmond, 1973). This additional polarization electric field can in some cases enhance the interchange motion driven by gravitational or inertial forces. These effects can become important for non-zero temperature plasmas, and they will be discussed in a future article.

Instead of a plasma density enhancement, let us now consider a "plasma hole" with a density smaller than the background intensity in the plasmasphere. In this case, the net external force is in the opposite direction, as for the buoyancy force acting on a bubble of air in water. Interchange velocity is then opposite to that of the direction of movement



FIG. 5. EQUATORIAL DRIFT PATH OF A 20 % PLASMA DENSITY ENHANCEMENT (SOLID LINE) AND OF A PLASMA HOLE WHOSE DENSITY IS 20% SMALLER THAN THE BACKGROUND DENSITY (DASHED LINE).

The maximum interchange velocity has been calculated from Gurevich *et al.* (1976) distribution for the integrated Pedersen conductivity. The E3H and M2 models have been used to determine the magnetospheric convection velocities. The square symbols mark the positions of the plasma elements every 5 h U.T. after their release at t = 00 U.T. at the equatorial distance of $R = 4 R_E$ in the local noon direction. The numbers near the squares indicate the U.T.'s. The size of the squares is proportional to the equatorial cross-section of the plasma elements. Note that the plasma density enhancement drifts inwards in the gravitational field, while the plasma hole spirals in the opposite direction toward an asymptotic trajectory.

of a plasma density enhancement. Interchange motion pushes a plasma hole outwards, when it is released inside the plasmasphere, as shown in Fig. 5. The outward spiraling dashed curve shows the drift path of a plasma element, with an initial density 20% smaller than the background density, that has been released at an equatorial distance of $4 R_E$ in the local noon sector. After somewhat more than 175 h the plasma element has completed six revolutions around the Earth. By that time, it has almost reached an asymptotic trajectory along which it can drift indefinitely if nothing else has changed in the meantime. The numbers given along the trajectory are the U.T.'s at which the plasma hole is located every 5 h after its initial release at t = 0.

Let us now consider a "plasma density enhancement", formed outside the plasmasphere at an equatorial distance of $7 R_E$ in the noon meridian plane. This element drifts beyond a Zero-Radial-Force Surface (ZRFS) analogous to the "Roche-Limit" surface introduced by Lemaire (1974, 1975). Beyond this critical surface (in the shaded area of Fig. 6), the radial component of the initial force exceeds the gravitational force. When averaged over one revolution around the Earth, the net external force on a plasma blob is directed away from the Earth. Since the drifting plasma density enhancement spends a rather long time beyond this Zero-Radial-Force-Surface, and less time in the region where the gravitational force dominates, the time-averaged interchange velocity will be directed outwards. Consequently, this drift path is an outward spiral, as shown by the solid line in Fig. 6. When this cold plasma element reaches the "Plasma Boundary Layer" or the magnetopause, it is considered to be lost (Nishida, 1966). The dashed line in Fig. 6 illustrates the equatorial drift path of



FIG. 6. Equatorial drift path of a 20 % plasma density enhancement (solid line) and of a plasma hole (dashed line) released at $R = 7 R_E$. Otherwise the conditions and notations are the same as in Fig. 5.

Note that the plasma density enhancement now drifts outwards. Under the dominating action of the centrifugal force whose radial component exceeds the gravitational force everywhere in the shaded area beyond the Zero-Radial-Force Surface. The plasma hole spirals in the opposite direction toward the same asymptotic trajectory as the plasma hole in Fig. 5. This asymptotic trajectory of all plasma holes determines the position of the equatorial plasmapause.

a "plasma hole" with an initial density 20% smaller than the background density. This element slips inwards toward the same asymptotic trajectory as the plasma holes coming from the inner plasmasphere (see Fig. 5). The asymptotic trajectories illustrated in Fig. 5 and 6 are identical. Therefore, all plasma holes forming anywhere in the magnetosphere ultimately accumulate along this asymptotic trajectory, whose shape and dimensions are quite similar to the equatorial plasmapause described by Carpenter (1966) and deduced from whistler observations.

FORMATION OF A PLASMAPAUSE

Figure 7 illustrates the mechanism of formation of a plasmapause as the consequence of interchange motion. Indeed, plasma holes both from inside and from outside the plasmasphere converge to, and accumulate along, a stable trajectory. The time average of the buoyancy force is zero along this final drift path along which a kncc in the background plasma density gradually forms.

The deeper the depression, the larger is the mass density difference (Δnm) between the inside and the outside of the plasma irregularity. Since the maximum interchange velocity is proportional to Δnm , plasma holes with the largest density defects move fastest, and they reach the asymptotic trajectory in a shorter time than those with smaller values for Δnm . This is illustrated in Fig. 7 where the interchange velocities corresponding to the deepest depressions are represented by the longest velocity vectors. A trough in the ambient density distribution forms most rapidly and most efficiently in the post-midnight sector where the interchange velocity is largest (because of the large convection velocity and centrifugal acceleration and secondly also because of the small Pedersen conductivity in the nightside region). Note that it is in the postmidnight L.T. sector that the asymptotic trajectory as well as the ZRFS both penetrate deepest in the inner magnetosphere.

Figure 1 probably shows a trough forming in the plasma density at $\varphi = 02:00$ L.T. and L=3.5. Trenches or plasma holes of this same kind can be found often in OGO 5 equatorial density distributions, even in the post-midnight sector and in the vicinity of the main plasmapause knee.

The large plasma enhancement in Fig. 7 formed beyond the stable asymptotic trajectory, ultimately moves outwards as a consequence of the outwardly directed buoyancy force beyond the ZRFS. This large plasma enhancement becomes a detached plasma element (or a plasma tail) which can be convected around the Earth toward the dayside and afternoon sector where Chappell (1974) has measured most of these plasma elements. In this region the dominating gravitational force tends to bring these plasma elements back closer to the plasmasphere. Furthermore, if the convection electric field intensity decreases with time, such detached plasma elements can eventually become reattached in the dusk region. Note that the interchange velocity in the dayside magnetosphere is relatively small because of the large Pedersen conductivity in the dayside ionosphere. Therefore, these detached elements are forced to follow more or less equipotential surfaces in the pre-noon and afternoon L.T. sectors.

As a consequence, it can be seen that according to the present scenario, a new plasmapause can be formed by interchange motion in the post-midnight sector where the convection electric field has its largest value. Furthermore, this theory is consistent with Carpenter's (1966) observations of a region of "new high density plasma" in the equatorial range of $4-5 R_E$ near 18:00 L.T. Indeed, this "new plasma region", forming the equatorial bulge of the



FIG. 7. ILLUSTRATION OF THE INTERCHANGE MOTION OF PLASMA HOLES MOVING TOWARD AN ASYMPTOTIC POSITION WHERE THE GRAVITATIONAL AND INERTIAL FORCES BALANCE EACH OTHER WHEN AVERAGED OVER ONE REVOLUTION AROUND THE EARTH.

A knee in the equatorial density is formed at this location where all plasma density depressions acccumulate. This is where a new plasmapause is forming. The piece of plasma beyond the new plasmapause becomes detached, and drifts outwards by interchange motion like any plasma enhancement in Fig. 5. It can become reattached subsequently if the convection electric field intensity decreases later in time.

plasmapause can well be interpreted as a large detached plasma element which subsequently becomes reattached to the corotating plasmasphere in the equatorial duskside region.

THE SUBSTORM INJECTION BOUNDARY

McIlwain (1974) and Mauk and McIlwain (1974) have shown that very low energy electrons and ions (1-10 eV) are consistently observed along the ATS 5 geostationary orbit at L.T.'s given by: $\varphi = 25.5-1.5K_p$, where K_p is the geomagnetic activity index. For $K_p = 1$, this "substorm injection boundary" is traversed at $\varphi = 24:00$ L.T. When K_p increases, the edge of this suprathermal particle boundary is met at earlier L.T.'s.

We suggest that this boundary coincides with the outermost trajectory of plasma holes whose drift path is tangent to the dusk flank of the magnetopause. Indeed, as illustrated in Fig. 8, all plasma density depressions formed outside the plasmasphere and drifting in the dusk region between the plasmapause and the magnetopause, are westward of the outermost trajectory which is tangent to the magnetopause near 17:00 L.T., and which is attached to the nightside plasmapause near midnight L.T. As a consequence of the mechanism described in the previous section and illustrated in Fig. 7, another cold plasma "knee" can be formed along this characteristic trajectory tangent to the magnetopause.

Along the westward side of this trajectory, the cold plasma density of ionospheric origin is expected to be larger than on the eastward side. This larger equatorial density in the dayside and dusk plasmatrough (\cong 5–50 cm⁻³) results from the small daytime refilling rate of mid-latitude magnetic flux tubes, while magnetic flux tubes drifting out of the Plasma Boundary Layer, at L.T.'s later than 1700 h, have not been refilled and are devoid of



Fig. 8. Equatorial drift path of three plasma holes released at 9.5, 11.5 and 13.5 $R_{\rm E}$ in the dusk meridian plane.

The difference between the density outside and inside of these plasma holes is equal to 5 cm^{-3} , in all three cases. The electric and magnetic field models are respectively the E3H and M2 models of McIlwain. The maximum interchange velocity has been evaluated with the values for the integrated Pedersen conductivity given by the empirical model of Gurevich *et al.* (1976). It can be seen that plasma holes formed in the afternoon plasmatrough, outside the plasmasphere, converge toward a boundary which has been identified with the "substorm injection boundary" introduced by McIlwain (1974). Along this boundary, where all plasma holes tend to accumulate, a secondary "knee" in the cold plasma density is likely to be formed due to interchange motion. The larger cold plasma density on the westward side of this boundary scatters the suprathermal electrons and ions drifting inwards from the magnetotail or from the Magnetospheric Plasma Boundary Layer. The drift paths of these plasma holes eventually tend toward the asymptotic trajectory, shown in Fig. 6 which coincides with the equatorial plasmapause.

cold ionspheric plasma; the larger cold density built up along the westward side of this boundary constitutes a background of particles within which higher energy electrons and ions, drifting from the Plasma Boundary Layer toward the inner region of the magnetosphere, are scattered in pitch angles by wave-particle interactions. On the eastward side of this secondary plasmapause, the cold plasma density of ionospheric origin is so small ($<1 \text{ cm}^{-3}$) that substorm injected electrons and ions with 90° equatorial pitch angles are not significantly scattered away from the equatorial plane. Consequently a large flux of these particles with 90° equatorial pitch angles can be measured in the region eastwards from this additional plasma "knee", while on the westward side the suprathermal particle flux is reduced and more isotropic because of the higher cold plasma density favouring wave-particle interactions.

Therefore it is suggested that the substorm injection boundary defined by McIlwain (1974) coincides with the outermost trajectory of plasma holes whose drift path is tangent to the magnetopause. Note that this is also the innermost trajectory of plasma holes drifting inwards from the dusk flank of the magnetopause toward the nightside plasmapause.

DISCUSSION AND CONCLUSION

It has been re-emphasized that plasma interchange motion plays a determining role in the formation of the equatorial plasmapause. The presence of a Zero-Radial-Force Surface, where the radial components of the gravitational and inertial forces balance each other determines the region of the magnetosphere where cold plasma becomes unstable with respect to interchange motion. The reduced value for the integrated Pedersen conductivity in the nightside sector contributes to increase the maximum interchange velocity (i.e. to enhance the difference between the electric field inside and outside a cold plasma element). The large centrifugal force and the reduced Pedersen conductivity in the post-midnight sector both contribute to enhance the plasmasphere peeling-off effect near 24:00 L.T.

There is another similar surface, called the "Roche Limit" surface (Lemaire, 1974, 1975), which penetrates into the magnetosphere near midnight at even lower L-values than the ZRF Surface. Along this surface the components of the gravitational and centrifugal forces *parallel* to the magnetic field direction, balance each other. Therefore, we suggest that this surface be called the "ZeroParallel-Force Surface" (ZPFS) instead of "Roche Limit". Along any magnetic flux tube penetrating through the ZPF Surface, the total potential energy has a minimum in the equatorial plane (Lemaire, 1974). Consequently, ionospheric plasma is expected to flow upwards in such a flux tube, and to accumulate in the equatorial potential minimum. The innermost point of penetration of the ZPF Surface determines, therefore, the location of the Light-Ion-Trough (LIT) where such an upward flow of ionization depletes the ion-exosphere and the upper ionosphere. The position of the LIT nearly coincides with the constant electric equipotential which is tangential to the ZPF Surface near midnight L.T. (Lemaire, 1974, 1975). Note that this equipotential surface is located at smaller L-values than the equatorial plasmapause; like the observed LIT, the shape of this equipotential surface is also less asymmetric in the dawn-dusk direction than the equatorial plasmapause.

The physical mechanism proposed for the formation of an equatorial plasmapause does not rely critically on the presumed existence of a stagnation point at dusk, where the convection and corotation electric fields exactly balance each other. It is not excluded that for large values of the dawn-dusk convection electric field, such a stagnation point might possibly exist and might determine a plasmapause as the "last closed equipotential". But even with such singular electric field distributions, interchange motion of plasma holes and plasma density enhancements always offer an alternative physical mechanism for the formation of a sharp knee in the cold magnetospheric plasma distribution.

Therefore, we conclude that the asymptotic trajectory of all plasma holes formed anywhere in the magnetosphere determines the equatorial plasmapause, including the substorm injection boundary which is its extension in the pre-midnight plasmatrough region.

The approximate dimensions and the dawn-dusk asymmetry in the shape of the equatorial plasmapause described by Carpenter (1966) have been recovered by using, in our model calculation (1) empirical electric field and magnetic field distributions deduced by McIlwain, from his particle observations on board of ATS 5, (i.e. without any *ad hoc* adjustment for the uniform dawn-dusk electric field intensity) as well as (2) an empirical model for the integrated Pedersen conductivity deduced by Gurevich *et al.* from observations at all latitudes and L.T.'s.

The finite temperature effect and field-aligned

ionization flow can slightly change the trajectories of plasma density elements shown in Figs. 5, 6 and 8, but these effects do not alter the general conclusions obtained here for a cold isolated plasma irregularity.

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