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Azimuthal plasma pressure gradient in quiet time plasma sheet

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[1] We have investigated the quiet-time azimuthal plasma pressure gradient in the plasma sheet at a radial distance of 10 R_E to 12 R_E using two THEMIS spacecraft that were in overlapping orbits during the 2008 THEMIS tail season. The equatorial plasma pressure is estimated by using the in-situ measurement of the plasma pressure and magnetic pressure based on pressure balance assumption. The results show a persistent duskward pressure gradient in the entire observed nightside region, which indicates upward field-aligned current from the ionosphere maps to this entire region. This current corresponds to the Region-2 current system in the post-midnight sector and the Region 1 current system in pre-midnight sector. The pressure gradients indicate that the upward field-aligned currents peak in the vicinity of midnight and decrease towards dusk and dawn, perhaps approaching zero near dusk. The downward Region-2 current system in the pre-midnight sector is expected to be located earthward of 11 R_E. **Citation:** Xing, X., L. R. Lyons, V. Angelopoulos, D. Larson, J. McFadden, C. Carlson, A. Runov, and U. Auster (2009), Azimuthal plasma pressure gradient in quiet time plasma sheet, *Geophys. Res. Lett.*, *36*, L14105, doi:10.1029/2009GL038881.

1. Introduction

[2] The temporal evolution and spatial gradients of the plasma sheet pressure are important for understanding plasma sheet dynamics and its electrodynamical coupling with the ionosphere. It has been well established that the plasma pressure typically decreases with increasing radial distance [e.g., *Spence et al.*, 1989; *Lui*, 2003; *Tsyganenko and Mukai*, 2003] tailward of r ~ 3–4 R_E. However, the azimuthal variation of the plasma pressure, which is important for the study of plasma sheet dynamics and the magnetosphere-ionosphere coupling and associated with the divergence of perpendicular current and field-aligned currents (FAC), is less well known.

[3] Previous studies have found a dawn-dusk asymmetric pressure profile for the near-Earth plasma sheet ($r \approx 10{\sim}20\ R_E$) due to the energy-dependent duskward magnetic drift [*Lyons and Samson*, 1992; *Wing and Newell*, 1998, 2000; *Wang et al.*, 2007]. The observations by *Wing and Newell* [1998] from ionospheric observations mapped to the equatorial plane using the *Tsyganenko*-89 magnetic field model showed two high pressure regions, one is slightly dawnward of midnight and the other is in the dusk sector, giving a pressure gradient toward dusk in the dawn and dusk sectors and a gradient toward dawn near midnight. The high pressure region in the dusk sector is also observed by *Wang et al.* [2007] in the plasma sheet for very quiet solar wind conditions (low density and velocity, strong northward IMFB_z). However, uncertainties are introduced by low-latitude observations and model-dependent mappings, and variations in solar wind conditions can change the pressure distribution in the plasma sheet, implying a need for in-situ measurement of the azimuthal pressure gradient under quiet solar wind condition in the CPS.

[4] The relation between pressure gradients and FAC density $j_\parallel$(positive towards the ionosphere) is expressed [*Grad*, 1964; *Vasyliunas*, 1970]

$$j_\parallel = \frac{B_i}{B_e}\hat{b}\cdot(\nabla_e V \times \nabla_e P) \qquad (1)$$

where $V = \int \frac{ds}{B}$ is the flux tube volume and P is the plasma thermal pressure. B_i and B_e are the magnetic field in the ionosphere and equatorial plane, respectively. $\hat{b}$ is the magnetic field direction. It is known that the gradient of both the thermal pressure and the flux tube volume generally point tailward. Thus the magnitude of the azimuthal component of these two gradients and their evolution greatly affects the FAC. Presently, the gradient of the flux tube volume can only be obtained from global magnetic field models. *Antonova and Ganushkina* [1997] showed statistically that the flux tube volume gradient is radially tailward with fairly small azimuthal component unless the plasma sheet is strongly disturbed. Thus the azimuthal component of $\nabla_e P$ should be a more important factor for studying the driving of FAC [e.g., *Wing and Newell*, 2000; *Lyons et al.*, 2003; *Stepanova et al.*, 2004]. Specifically, within the quiet time plasma sheet, when the azimuthal component of flux tube volume gradient is expected to be quite small, the azimuthal pressure gradient is a critical indication of the driving of FAC. It should be remembered, however, that the necessity of using a magnetic field model adds uncertainty to the calculation of FAC from measurements of pressure gradients within the plasma sheet as well as does the assumption of isotropy in (1). The non-active-time FAC pattern mapped to the equatorial plane has been investigated by *Potemra* [1976] and *Antonova et al.* [2006] by mapping the *Iijima and Potemra* [1976b] ionospheric observations to the equatorial plane using different magnetic field models; and also by *Wing and Newell* [2000] using their mapped ionospheric observations. These will be discussed later in reference to Figure 4.

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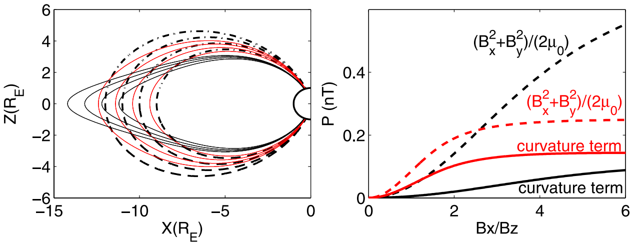

Figure 1. Estimate of the magnetic pressure and curvature terms in (2) for stretched and near-dipolar magnetic field. (left) Magnetic field lines. Black solid is for stretched field, and red solid is for near-dipolar and dashed for dipolar configuration. (right) Comparison of the pressure/curvature terms versus the distance from the equatorial plane. Black is for the stretched field, and red is for the near-dipolar field.

[5] Measurement of the azimuthal pressure gradient is now possible with the THEMIS multi-point spacecraft mission. We take advantage of the two THEMIS probes THD and THE, which are closely space in nearly the same orbit with apogees of ∼11 R$_E$ to calculate the azimuthal pressure gradient for the quiet-time plasma sheet. To reduce the error of estimating central plasma sheet thermal pressure from the in situ observations, a simple formula is introduced in Section 2. In Section 3, the data sets for pressure gradient are shown and some preliminary interpretations are given. Our results are summarized in Section 4.

2. Dataset and Methodology

[6] We have used data from December 2007 to May 2008, when the THEMIS probes were mostly in the magnetotail with their apogees sweeping the night-side region. The high resolution (3 seconds) on board particle data are used from the ESA (Electrostatic Analyzer) and SST (Solid State Telescope), which cover the particle energy range 5eV to 6MeV for ions and 5eV to 1MeV for electrons [*Angelopoulos*, 2008; *McFadden et al.*, 2008]. Magnetic field data are from Flux Gate Magnetometer (FGM) [*Auster et al.*, 2008]. Quiet times were identified as having no obvious aurora signatures (from THEMIS All-Sky Imagers) and no substantial ground magnetic perturbations ($\Delta B_x > 100$ nT at more than one ground stations) for at least 2 hrs before and after spacecraft apogee. 28 examples were identified using this criterion during the 2008 tail season.

[7] Since the probes are not always located near the equatorial plane, we assume vertical pressure balance in the plasma sheet for isotopic pressure, i.e., $\nabla P = \frac{1}{\mu_0}(\nabla \times \vec{B}) \times \vec{B}$. Assuming that the dawn-dusk asymmetry of the magnetic field is not large, i.e., $\frac{\partial}{\partial y} = 0$, integrating the force balance equation vertically gives:

$$P_0 = P_z + \frac{B_x^2 + B_y^2}{2\mu_0} - \frac{1}{\mu_0}\int_0^z \frac{\partial B_z}{\partial x} B_x dz \tag{2}$$

where P_0 is the equatorial thermal pressure. All the parameters on the RHS are measurable except for the third term. The integral cannot be calculated accurately without a 3D realistic magnetic field model. However, for tail-like magnetic field configuration, which generally holds for our region, the third term should be small compare to the second term. To address the role of these two terms, we do a simple calculation. Figure 1 shows the two terms calculated using the *Tsyganenko and Stern* [1996] magnetic field model. Figure 1 (left) shows example field line configurations in the midnight meridian plane, the black solid lines, the red solid lines and the dashed lines representing, respectively, a typical quiet-time stretched field ($B_y = 0$, $B_z = 2$ nT, $n_{sw} = 5$ cm^{-3}, $v_{sw} = 400$ km/s, Dst = 0, referred from OMNIWeb on ∼07:00 February 26, 2008), a near-dipolar field ($B_y = 0$, $B_z = -3$ nT, $n_{sw} = 1.5$ cm^{-3}, $v_{sw} = 600$ km/s, Dst = −25 nT, artificial numbers to generate a near-dipolar field), and a pure dipole. Figure 1 (right) displays the magnetic pressure and curvature terms for the two non-dipolar magnetic configurations versus distance from the equatorial plane (represented by B_x/B_z) at r = 11 R$_E$. The two terms increase with increasing distance from the equatorial plane but the magnetic force term is always substantially larger than the curvature term especially for the stretched field. Thus for realistic field configurations more stretched than a dipole field, the third term in (2) can be ignored compared to the second term. Notice that for a pure dipole field the second and the third terms in (2) cancel and the pressure balance assumption no longer holds.

3. Data Analysis

[8] We calculate the azimuthal pressure gradient using

$$\nabla_\theta P = 2(P_{THD} - P_{THE})/[(R_{THD} + R_{THE})|\theta_{THD} - \theta_{THE}|] \tag{3}$$

$P_{THD/THE}$ are the estimated equatorial plasma pressures from THD and THE as obtained from (2) by dropping the third term. $R_{THD/THE}$ and $\theta_{THD/THE}$ are the radial distances and the azimuthal angles of the spacecraft locations. Since THD is always dawnward of THE within ±5 hrs of apogee, and positive and negative values of (3) represent dawnward and duskward pressure gradient, respectively. To minimize the radial effect on this two-point calculation, we define ‘apogee’ as the position where the radial difference between the two probes is a minimum, and focus on the region around this azimuthally lined up position, which is very close to the real apogee of the orbit of each spacecraft.

[9] Figure 2a shows the equatorial pressure from THD and THE together with their azimuthal pressure gradient during a 5 hr quiet period on January 03, 2008 with the spacecraft apogee in the dawn sector. Spacecrafts location (in GSM) and MLT are given below the plot. Red and black curves in Figure 2a (top) give the estimated equatorial plasma pressure for THD and THE, respectively. ‘Apogee’ is identified by the vertical line. The pressure shows a quite steady pattern and the dawnward probe THD always sees lower pressure during this time interval. Thus the azimuthal pressure gradient in Figure 2a (bottom) is negative for the whole time interval. With a tailward flux tube volume gradient, this indicates an upward FAC from the ionosphere. This example represents 9 other cases in the dawn sector.

[10] In Figure 2b the same quantities are shown for an orbit with apogee close to midnight (on February 05, 2008). The pressure difference between the spacecraft again shows

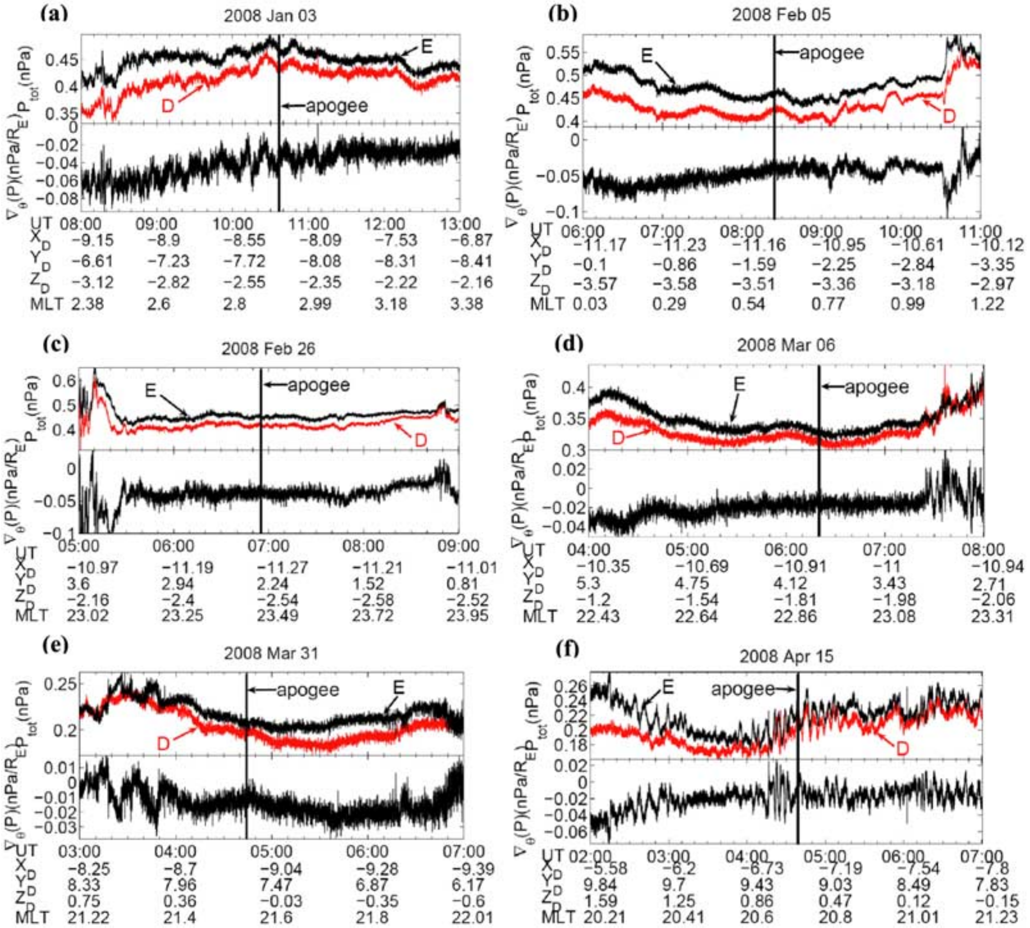

Figure 2. (top)The estimated equatorial plasma pressure of THD and THE and (bottom) the azimuthal pressure gradient in GSM coordinates: (a) apogee in dawn sector, (b) apogee near midnight, and (c)–(f) apogee in dusk sector.

a steady negative gradient of approximately the same magnitude as seen in the dawn sector. There are four other quiet cases with apogee within 1 hr of midnight, and they show the same signature. The results in Figures 2a and 2b agree with the *Potemra* [1976] and *Antonova et al.* [2006] studies that the magnetic drift causes duskward directed pressure gradients from dawn to midnight. However, the data from the 2008 nightside THEMIS season do not show a reversal of the azimuthal pressure gradient on the dusk side of midnight expected by these studies. Figures 2c–2f show four selected quiet-time plasma sheet periods with spacecraft apogee near 23.3MLT, 22.5MLT, 21.3MLT and 20.5MLT, respectively. All of these cases show duskward azimuthal pressure gradients, although the magnitude of the duskward gradient tends to decrease as the apogee moves toward dusk. These results agree with *Wing and Newell* [2000] mapping results that the pressure gradient is directed duskward in the dusk sector at ∼11R_E.

[11] Figure 3 shows the quiet-time azimuthal pressure gradients versus MLT measured during the entire 2008 tail season with each point representing one apogee position. Although there are some individual outlying points (e.g., the peak near 2.5 MLT; the dip near 21 MLT), the data indicate a quite clear trend. The strongest azimuthal gradient, and thus the strongest FAC out of the ionosphere, is located in the midnight to slightly post-midnight region. The pressure gradient reduces toward both dawn and dusk. There is also evidence that the magnitude of the gradient decreases more towards dusk than towards dawn, and that the gradient approaches zero near dusk. This result agrees with *Wang et al.* [2007] in the pre-midnight sector. Note that we are interested here in the azimuthal component because of its importance for FAC, though, as noted by *Wing and Newell* [2000], the largest pressure gradient in the equatorial plane is directed radially.

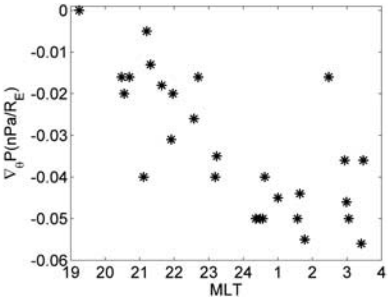

Figure 3. The estimated value of azimuthal pressure gradient versus MLT for all quiet-period in the 2008 THEMIS tail season.

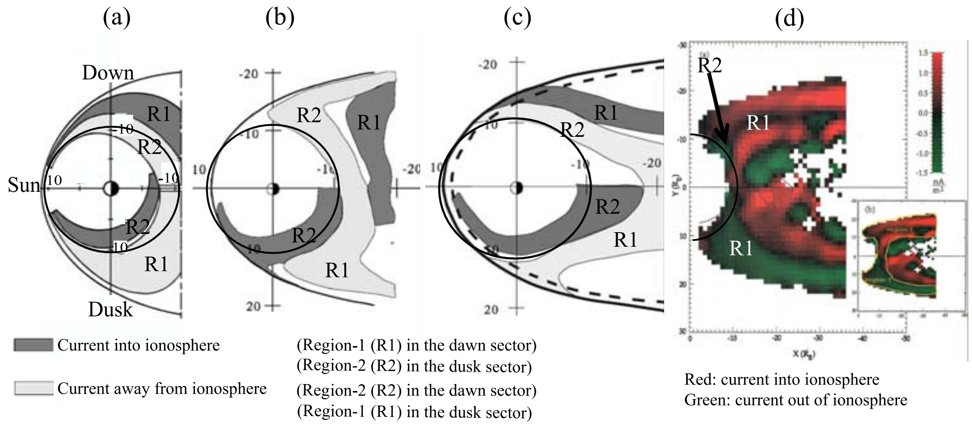

Figure 4. (a) The *Iijima and Potemra* [1976b] quiet time FAC pattern as mapped to the equatorial plane using the *Fairfield and Mead* [1975] magnetic field model (adopted from *Potemra* [1976]), (b) and (c) the Tsyganenko 2001 model and the Tsyganenko 1996 model (both adopted from *Antonova et al.* [2006]), and (d) the *Wing and Newell* [2000] FAC mapped to equatorial plane (adopted from *Wing and Newell* [2000]). The superposed black circle gives r = 11 R_E from the Earth.

[12] This initial picture of the azimuthal current pattern in the inner plasma sheet indicates that there should be upward FAC everywhere on the nightside at 11 R_E. In Figure 4 we compare our equatorial results at $\sim$11R_E with previous works by highlighting the r = 11R_E circle in those results. Figures 4a–4c show, respectively, the quiet-time FAC observed by *Iijima and Potemra* [1976b] mapped to the equatorial plane using the *Fairfield and Mead* [1975] magnetic field model (by *Potemra* [1976]), the Tsyganenko 2001 magnetic field model, and the Tsyganenko 1996 magnetic field model (the latter two by *Antonova et al.* [2006]). The mapping with the Fairfield and Mead model is most consistent with our observations, with the Region-2 system in the post-midnight sector and the Region-1 system in the pre-midnight sector both giving upward FAC from the ionosphere mapping to 11 R_E. The mapping of the region of upward FAC on the nightside from the Tsyganenko 2001 model is only slightly beyond 11 R_E, whereas the more highly stretched Tsyganenko 1996 model maps this region to well beyond our observation location.

[13] The *Wing and Newell* [2000] results (Figure 4d) agree with our observations in the dusk to near midnight region and dawnward of $\sim$2 MLT. However, they found a post-midnight region of downward FAC near where our results show a strong upward FAC. This disagreement may result from the different quiet-time selection criteria or from the small statistics in our present study. It also could be from the model-dependent mapping uncertainties, since agreement with *Wing and Newell*'s [2000] results is better in the region earthward of 11 R_E. The mappings in Figure 4 suggest that a transition from upward Region-2 FAC on the pre-midnight side to downward Region-2 FAC on the post-midnight side should be seen closer to the Earth, and evidence that this is the case has been presented by *Iijima et al.* [1990] using AMPTE CCE magnetic field measurements.

4. Concluding Remarks

[14] We have investigated the nightside plasma azimuthal pressure gradient in the equatorial plane at r $\sim$ 11 R_E for the quiet time plasma sheet using observation during the first THEMIS tail season from THD and THE spacecraft, which have overlapping orbits. The equatorial plasma pressure was estimated from the in situ measurement of plasma pressure and magnetic pressure by assuming pressure balance. The results indicate that the pressure gradient is generally duskward over the entire nightside, although the magnitude of the gradient decreases more towards dusk than towards dawn and seems to approach zero near dusk. Such a gradient is associated with FAC flowing out of the ionosphere, which would correspond to the Region-2 current system in the post-midnight sector and the Region-1 current system in the pre-midnight sector being mapped to this radial distance. This suggests that nightside portions of what are referred to as Region-1 and Region-2 current systems both map to the inner plasma sheet and are connected to duskward directed pressure gradients, indication the possibility that these are physically part of the same current system.

[15] The results presented here should be regarded as preliminary. More data are needed to obtain a more complete and statistically reliable picture of the current pattern as a function of MLT, and should be available after multiple years of THEMIS measurements. These initial results show the pressure gradient approaching zero near dusk, so that with more data, it will be interesting to determine if a statistically significant peak of pressure can be found at some MLT region on the afternoon-to-evening side at r $\sim$ 11 R_E, or whether, as suggested by the mapping to the equatorial plane in Figure 4a, the magnetopause is encountered so that the pressure gradient within the magnetosphere at r $\sim$ 11 R_E is always directed towards earlier MLT.

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