Comparison of energetic electron flux and phase space density in the magnetosheath and in the magnetosphere

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[1] Whether energetic electrons (10s of keV) in the magnetosheath can be directly transported into the magnetosphere and further energized through radial diffusion is significant in understanding the physical mechanisms for producing the radiation belt electrons (>100s of keV) in the magnetosphere. In this study, we analyze more than two hundred magnetopause crossing events using the energetic electron and magnetic field measurements from Geotail and compare the flux and phase space density (PSD) of the energetic electrons on both sides of the magnetopause. It is found that for most of the events (>70%), the fluxes and PSDs of energetic electrons in the magnetosheath are less than those in the magnetosphere, suggesting that the energetic electrons in the magnetosheath cannot be a direct source sufficient for the energetic electrons inside the magnetosphere. In fact, our analysis suggests a possible leakage of the energetic electrons from inside to outside the magnetopause. By investigating the average energetic electron flux distribution in the magnetosheath, we find that the energetic electron fluxes are higher near the bow shock and the magnetopause than in between. The high energetic electron flux near the bow shock can be understood as due to energization of electrons when they go through the bow shock. The relatively low flux of the energetic electrons in between indicates that it is difficult for the energetic electrons to travel from the bow shock to the magnetopause and vice versa, possibly because the energetic electrons near the bow shock and the magnetopause are all on open magnetic field lines and these two relatively intense energetic electron populations in the magnetosheath rarely get mixed.

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1. Introduction

[2] The shape of the magnetosphere is determined by the Earth's internal magnetic field, the solar wind plasma, and the interplanetary magnetic field (IMF). It is well known that the solar wind plasma can be transported and energized through the bow shock and into the magnetosheath, and some of the plasma may further enter the magnetosphere. An important energetic electron population inside the magnetosphere resides in the outer radiation belt, which consists of electrons with hundreds of keV to MeV energies. It has been observed for many years that the intensity of energetic electrons in the outer radiation belt varies with the upstream solar wind [*Baker et al.*, 1986; *Li et al.*, 1997a; *Li and Temerin*, 2001; *Li et al.*, 2011] and geomagnetic activity [*Reeves*, 1998; *McAdams et al.*, 2001; *Reeves et al.*, 2003].

[3] The origin of the outer radiation belt electrons remains an unsolved problem. To understand this problem it is necessary to review some physical properties of the outer radiation belt and the basic processes that are considered important in controlling its dynamics [e.g., *Li et al.*, 1997b; *Li and Temerin*, 2001; *Millan and Thorne*, 2007]. Several mechanisms have been proposed for the source of the outer radiation belt and its subsequent acceleration [e.g., *Friedel et al.*, 2002]. Two main acceleration mechanisms are radial diffusion and local heating by VLF whistler waves [*Baker et al.*, 1998; *Hudson et al.*, 2000; *Barker et al.*, 2005; *Bortnik and Thorne*, 2007; *Tu et al.*, 2009]. Radial diffusion requires an exterior source, such as from the solar wind [*Li et al.*, 1997b] or the outer magnetosphere [e.g., *Li et al.*, 2001; *Elkington et al.*, 2003]. *Li et al.* [1997b] have demonstrated that although lower energy electrons in the solar wind could be a seed population of the outer radiation belt, such lower energy electrons cannot achieve relativistic energies through the normal process of radial transport which conserves the first adiabatic invariant. But, when the solar wind plasma are transported through the bow shock into the magnetosheath, the electrons can be energized [*Thomsen et al.*, 1987; *Gosling et al.*, 1989; *Lowe*

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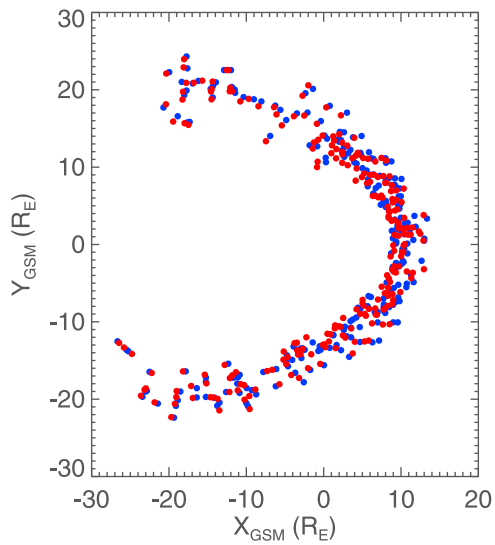

Figure 1. Positions of the measurements in the magnetosheath and in the magnetosphere for 235 magnetopause crossing events in the GSM coordinates. The magnetosheath and the magnetosphere measurements are shown in blue and red, respectively.

and Burgess, 2000]. Could these heated electrons be further transported through radial diffusion into the outer magnetosphere near the magnetopause and finally supply the seed electrons for inner magnetosphere? If the electrons in the magnetosheath are not the source of energetic electrons in the outer magnetosphere, then there should be other acceleration processes within the magnetosphere which, for some reasons, are well correlated with solar wind variations (*Burin des Roziers et al.* [2009] and *Luo et al.* [2011] found that the energetic electron flux in the magnetosphere has great correlation with the upstream solar wind speed and southward magnetic field). In the present study, based on the electron measurements inside and outside the magnetopause when Geotail crossed the magnetopause, we make a direct comparison between the energetic electron flux and electron PSD in the magnetosheath and in the magnetosphere, in order to address the important question of whether the electrons in the magnetosheath could be a direct source sufficient for energetic electrons in the outer magnetosphere.

2. Instrumentation

[4] The magnetopause crossings are identified by Geotail satellite measurements. A total of seven years' Geotail data are used, ranging from 1998 through 2004. The Geotail satellite was launched in 1992 into an eccentric near equatorial orbit, to explore the dynamics of the magnetotail over a wide range of distances. During the period from 1998 to 2004, Geotail was in an orbit with an apogee of 30 R_E and a perigee of 9 R_E. The position of Geotail's apogee rotates around the earth periodically on the near equatorial plane, which provides magnetopause crossing events on the dawn-noon-duck sector studied in this paper. Particle and magnetic field measurements are used for the study. Particle data are from two instruments: the Energetic Particle and Ion Composition (EPIC) [*Williams et al.*, 1994] instrument, which measures the >38 keV and >110 keV integral electron flux, and the Comprehensive Plasma Instrument (CPI) [*Frank et al.*, 1994], which provides the ion density and temperature. The magnetic field measurements are obtained from the fluxgate magnetometer (MGF) [*Kokubun et al.*, 1994]. The time resolution of Geotail data used in this study is 15 min.

3. Data Selection

[5] In order to compare the energetic electron flux and PSD in the magnetosheath and in the magnetosphere, we first need to collect the measurements on each side of the magnetopause when the Geotail crossed the magnetopause. For the purpose of our study, we do not need to find out exactly when the Geotail crossed the magnetopause, but rather to identify the nearest pair of the measurements during the crossing, with one inside the magnetosheath and the other inside the magnetosphere, satisfying our selection criteria, which will be described later. The properties of the magnetosheath and magnetosphere plasma near the magnetopause have been widely studied [e.g., *Paschmann et al.*, 1993; *Sibeck and Gosling*, 1996; *Phan et al.*, 1994; *Phan and Paschmann*, 1996]. The magnetosheath is a region between the magnetopause and the bow shock, where the ion temperature is low but the ion density is high (cold and dense), while on the other side of the magnetopause, in the magnetosphere, the ion temperature increases and the ion density decreases (hot and tenuous). In this study, measurements with low ion temperature, $T_i <$ 200.0 eV, and high density, $N_i > 10.0$ cm^{-3}, are considered to be inside the magnetosheath while measurements with high ion temperature, $T_i >$ 1000.0 eV, and low density, $N_i <$ 2.0 cm^{-3}, are considered to be inside the magnetosphere. Even though with these strict selection criteria, we may miss some magnetosheath intervals that have lower density or higher temperature (similarly for the magnetosphere selections), these criteria will reliably select the measurements inside the magnetosheath and inside the magnetosphere. Furthermore, since the magnetosheath and magnetosphere are very dynamic, in each Geotail magnetopause crossing, the nearest pair of magnetosheath and magnetosphere measurements are collected only if they are measured within one hour by Geotail. The strict criteria may result in the two paired observations not being adjacent 15-minute samples (there might be one or two in between that don't meet the density and temperature criteria as the magnetopause transition is crossed and intermediate values are measured), but that the one-hour criterion should ensure that no major dynamics occurred as the observations settled down from one regime to the other. Under these criteria, from 1998 to 2004, 235 magnetopause crossing events are collected, with each crossing event corresponding to a pair of qualified measurements. The positions of the magnetosheath and the magnetosphere measurements during these magnetopause crossings are shown in Figure 1, with the measurements in the magnetosheath in blue and the measurements in the magnetosphere in red. There are 115 events on the dawn side, and 120 events on the dusk side.

4. Flux and Phase Space Density (PSD) Comparison

[6] With the Geotail database, we compare the energetic electron flux and PSD in the magnetosheath and in the

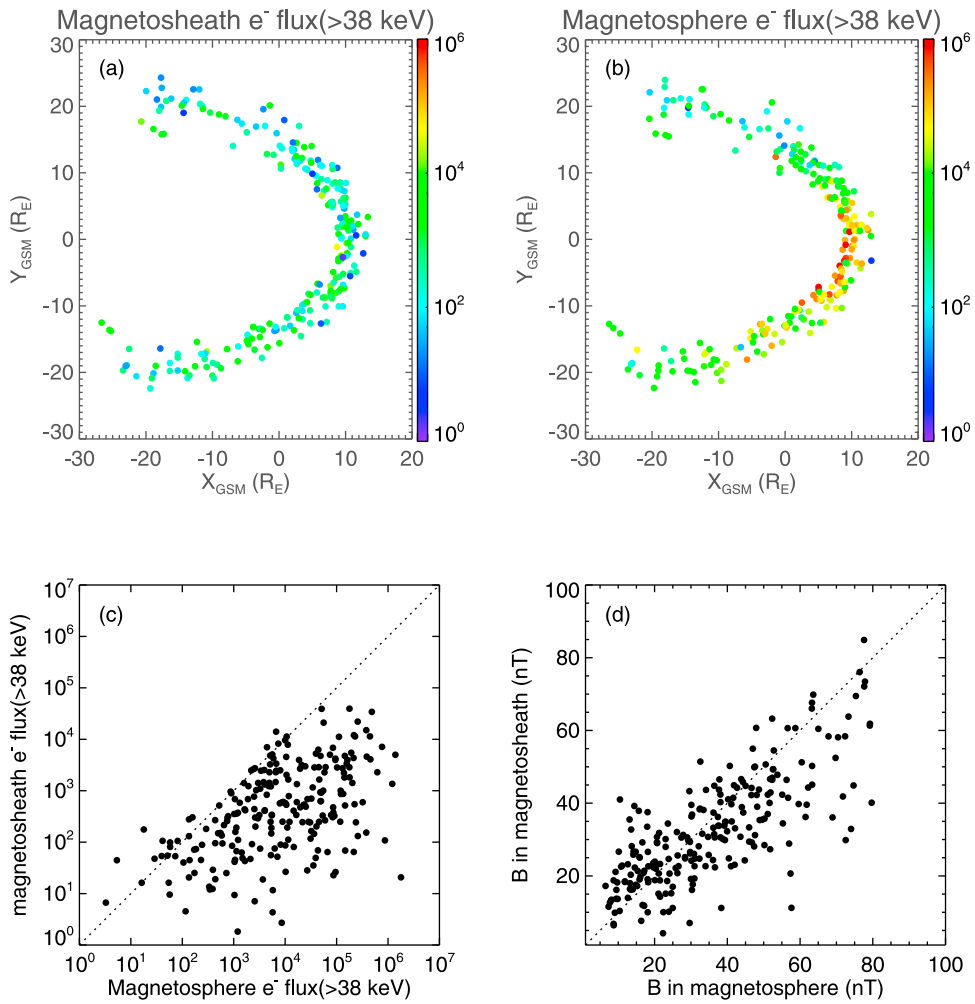

Figure 2. The energetic electron flux measurements (a) in the magnetosheath and (b) in the magnetosphere for the selected magnetopause crossing events. (c and d) The comparisons of energetic electron flux and magnetic field strength in the magnetosheath and in the magnetosphere.

magnetosphere. Figures 2a and 2b show the measured >38 keV electron fluxes in the magnetosheath and in the magnetosphere, respectively. The dawn-dusk asymmetry of the energetic electrons in the magnetosphere agrees with the results from previous studies showing that the trapped tens of keV electrons dominate the dawn side [*Imada et al.*, 2008; *Luo et al.*, 2011]. The same dawn-dusk asymmetry of energetic electron flux also exists in the magnetosheath though weaker than in the magnetosphere. This will be further discussed later in this paper. Figure 2c shows the flux comparison between these two populations. It can be seen that the >38 keV electron fluxes are generally higher in the magnetosphere than in the magnetosheath. If the magnetic field strengths were comparable in the magnetosheath and the magnetosphere then Figure 2c, which shows higher fluxes inside and lower fluxes outside the magnetopause, would already suggest that the electrons in the magnetosheath are not a sufficient source for the electrons in the magnetosphere (if the magnetic field strengths were comparable in magnetosheath and the magnetosphere then the two fluxes measured at the same energies would be proportional to two PSDs at the same values of the first adiabatic invariant). However, the magnetic field strength measured by Geotail in the magnetosheath and in the magnetosphere shows that the magnetic field strength in the magnetosphere is generally different from (and on average stronger than) that in the magnetosheath, as shown in Figure 2d. Therefore, we should compare the electron PSD for the same first adiabatic invariant (μ) on both sides of the magnetopause to see whether the magnetosheath has a higher PSD, which would indicate a source region, than the magnetosphere.

[7] The PSD, f, and differential flux, j, are related by

$$f = \frac{j}{E(E + 2m_0c^2)} \cdot \left[1.66 \times 10^{-10}\right] \times 200.3, \qquad (1)$$

where f is PSD in GEM (Geospace Environment Modeling) units (c/MeV/cm)^3, j is electron differential flux in unit of cm^{-2} sr^{-1} s^{-1} keV^{-1}, E is energy in MeV, and m_0c^2 is the rest energy of an electron. For a detailed discussion of equation (1), see *Chen et al.* [2005; also see *Turner and Li*, 2008]. The first adiabatic invariant, μ, is calculated by

$$\mu = \frac{E(E + 2m_0c^2)}{B(2m_0c^2)} \times 10^5 \left[\frac{MeV}{G}\right], \qquad (2)$$

where B is the magnetic field strength in nT measured by Geotail. For μ calculation, we assume an isotropic electron

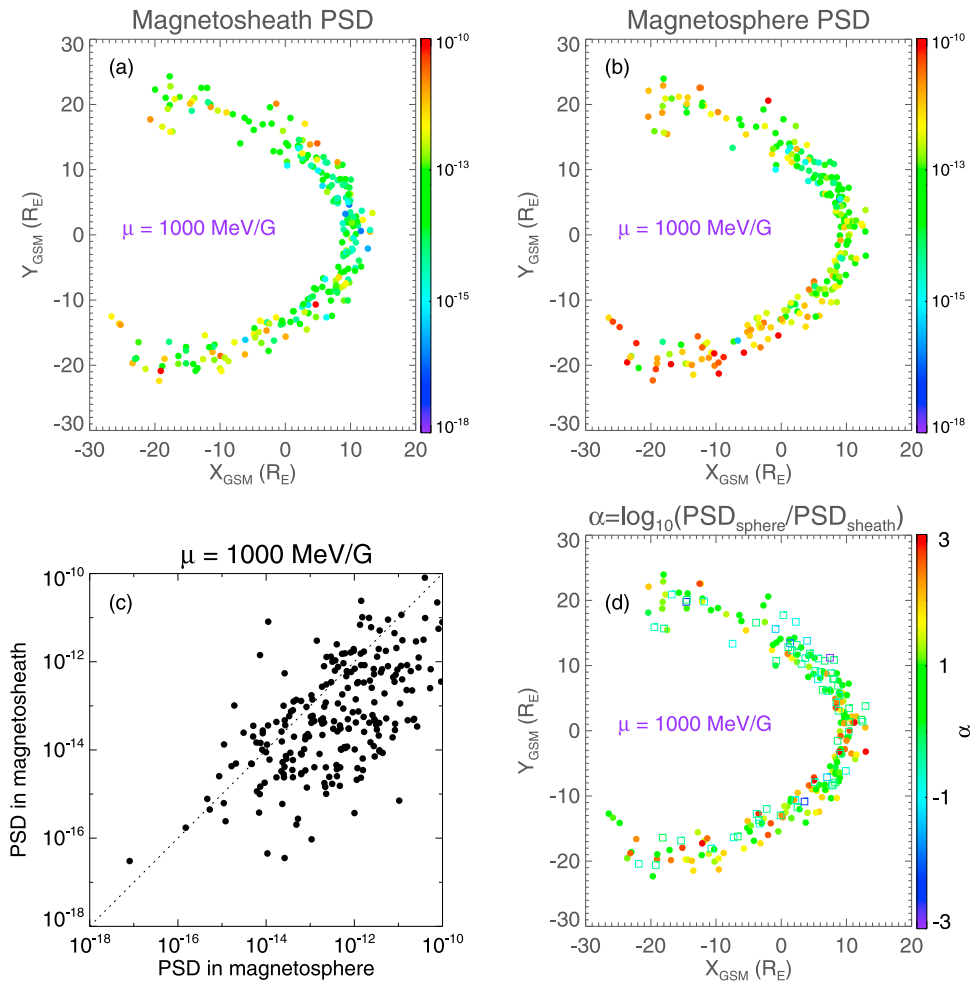

Figure 3. The electron phase space density (PSD) of μ = 1000 MeV/G at the selected points (a) in the magnetosheath and (b) in the magnetosphere. (c) The comparison of PSDs in scatter plot and (d) the log of the ratio of PSDs in the magnetosphere and in the magnetosheath. The points where PSDs are higher in the magnetosphere are indicated as colored dots in Figure 3d, while points where PSDs are higher in the magnetosheath are indicated as colored squares.

distribution since electron pitch angle is not resolved in the data. This assumption has been widely used in research on magnetospheric dynamics [e.g., *Hilmer et al.*, 2000; *Taylor et al.*, 2004; *Burin des Roziers et al.*, 2009], and is also supported by various works in the magnetosheath [e.g., *Lavraud et al.*, 2009; *Lu et al.*, 2011]. For the energetic electron flux, j, the Geotail/EPIC have two integral fluxes, >38 keV and >110 keV, while differential flux is required to calculate PSD. The differential flux is estimated by assuming the energy spectra of electrons varies as a power law $j = AE^{-\lambda}$ [*Burin des Roziers et al.*, 2009; *Luo et al.*, 2011]. The A and λ can be determined using the following formula:

$$j_{>38} = \int_{38}^{\infty} AE^{-\lambda} dE, \qquad j_{>110} = \int_{110}^{\infty} AE^{-\lambda} dE \qquad (3)$$

which leads to

$$\lambda = 1 - \frac{\log_{10} \frac{j_{>38}}{j_{>110}}}{\log_{10} \frac{38}{110}}, \qquad A = j_{>38} \times \frac{(\lambda - 1)}{38^{1-\lambda}} \qquad (4)$$

where $j_{>38}$ and $j_{>110}$ are measured >38 keV and >110 keV integral fluxes, A is a constant, and λ is the instantaneous power law index for each time step.

[8] The calculated electron PSDs for μ = 1000 MeV/G are shown in Figure 3, with Figure 3a for the magnetosheath and Figure 3b for the magnetosphere. μ = 1000 MeV/G corresponds to electron's energy to be 307 keV for a typical magnetic field value of B = 40 nT. It can be seen that similar to the energetic electron flux distribution, the dawn-dusk asymmetry also exists for the PSDs in the magnetosheath and magnetosphere, with higher PSDs on the dawn side. The comparison of the calculated electron PSD for μ = 1000 MeV/G in the magnetosheath and in the magnetosphere is shown in Figure 3c. For 169 of the 235 magnetopause crossing events (72% in percentage) studied in this study, the PSDs are higher in the magnetosphere than in the magnetosheath. For the other 66 events (28% in percentage), the PSDs are higher in the magnetosheath. The spatial distribution of the comparison result is shown in Figure 3d. The probability of higher PSDs in the magnetosphere than in the magnetosheath also shows dawn-dusk asymmetry. 79% of

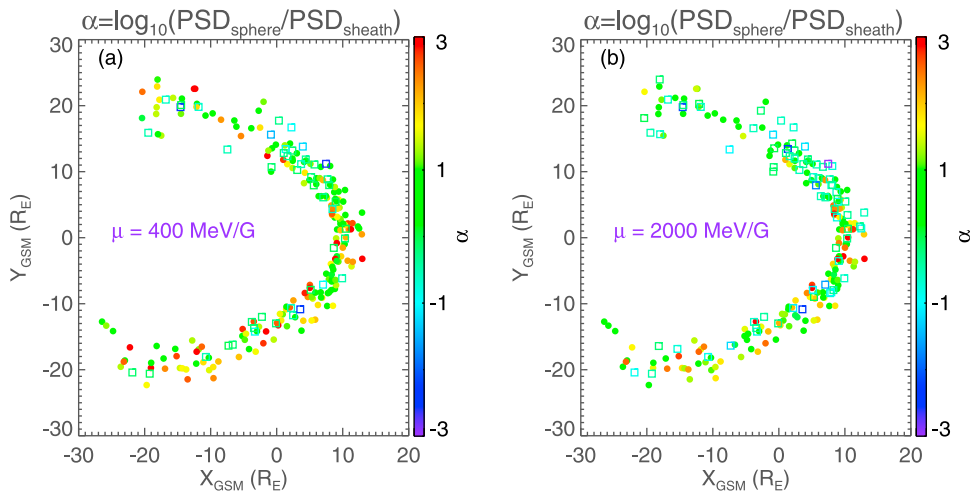

Figure 4. PSD comparisons in the magnetosphere and in the magnetosheath for (a) μ = 400 MeV/G and (b) μ = 2000 MeV/G (same format as Figure 3d).

the 115 magnetopause crossing events on the dawn side show higher PSDs in the magnetosphere than in the magnetosheath, while 65% of the 120 events on the dusk side show so. We also looked at other μ values and the results were similar. Figure 4 shows the PSD comparisons for μ = 400 MeV/G and μ = 2000 MeV, which correspond to electron's energies of 140 keV and 527 keV for typical magnetic field B = 40 nT. For the total 235 events, the percentages of events with higher PSDs in the magnetosphere than in the magnetosheath are 80% and 69%, respectively, for each μ. The dawn-dusk asymmetry still exists, with the percentage of higher PSDs on the dawn side larger then on the dusk side. Based on these results, we suggest that the electrons in the magnetosheath are not a direct source adequate to account for all energetic electrons in the magnetosphere through normal radial transport, and additional acceleration precesses inside the magnetosphere are required to produce the observed energetic electrons inside the magnetopause.

5. Leakage of Electrons From the Magnetosphere to the Magnetosheath

[9] The higher energetic electron fluxes and PSDs in the magnetosphere than in the magnetosheath may actually lead to the leakage of electrons from inside to outside the magnetopause. The leakage of magnetospheric particles, such as He^+ and O^+, has been proven by observation and widely studied for many years [see, e.g., *Chen and Moore*, 2004; *Fujimoto et al.*, 1997; *Fuselier et al.*, 1989; *Gosling et al.*, 1990; *Peterson et al.*, 1982; *Taylor and Lavraud*, 2008]. There is no reason why the energetic electrons inside magnetopause, which have higher flux and PSD, cannot leak into the magnetosheath. However, based on observations it is hard to prove the leakage of electrons because electrons can be found in both the magnetosphere and magnetosheath, not like He^+ and O^+, which are magnetospheric species and seldom exist in the solar wind. To investigate whether the electrons can leak into the magnetosheath, we calculated the spatial distribution of energetic electron flux in the magnetosheath measured by Geotail from 1998 to 2004. During the period, the magnetosheath measurements are selected according to our magnetosheath criteria described before, low ion temperature, $T_i < 200.0$ eV, and high density, $N_i > 10.0$ cm^{-3}, plus further selection on the ion bulk speed. Specifically, we compare the ion speed measured by Geotail with solar wind speed measured by ACE satellite. Those Geotail measurements on the dayside which have high ion speed (greater than 300 km/s) and are comparable with ACE solar wind speed are further excluded. Figure 5a shows the distribution of all the selected Geotail flux measurements in the magnetosheath. We further average the selected measurements on a 2 × 2 R_E grid on the GSM XY plane and show the flux distribution in Figure 5b. It shows that clearly there are two high flux regions, one near the bow shock and the other near the magnetopause, although the data numbers in these two regions are less than in between (Figure 5d). Between the two high flux regions the energetic electron fluxes are low. The relatively high energetic electron flux near the bow shock can be understood as due to energization of electrons in the solar wind while going through the bow shock [*Thomsen et al.*, 1987; *Gosling et al.*, 1989; *Lowe and Burgess*, 2000]. The other high flux region near the magnetopause in the magnetosheath may be due to the leakage of energetic electrons from the magnetosphere. Furthermore, the dawn-dusk asymmetry of energetic electron flux in the magnetosheath is clearly seen in Figure 5b. Considering the dawn-dusk asymmetry of the flux and PSD in the magnetosphere (Figures 2b and 3b), as well as the higher percentage of PSD ratio lager than one in dawn sector than in the dusk (Figures 3d and 4), the suggested leakage of energetic electrons from the magnetosphere to the magnetosheath is further supported. These two high-flux electron populations appear to mix rarely if at all, as suggested by the low electron flux region in between, though the average PSD shows decrease when getting closer to the magnetopause (Figure 5c). This is perhaps because the magnetic field lines in the magnetosheath are open and the electrons in the magnetosheath are not trapped, very few electrons energized from the bow shock can reach the magnetopause, and very few electrons

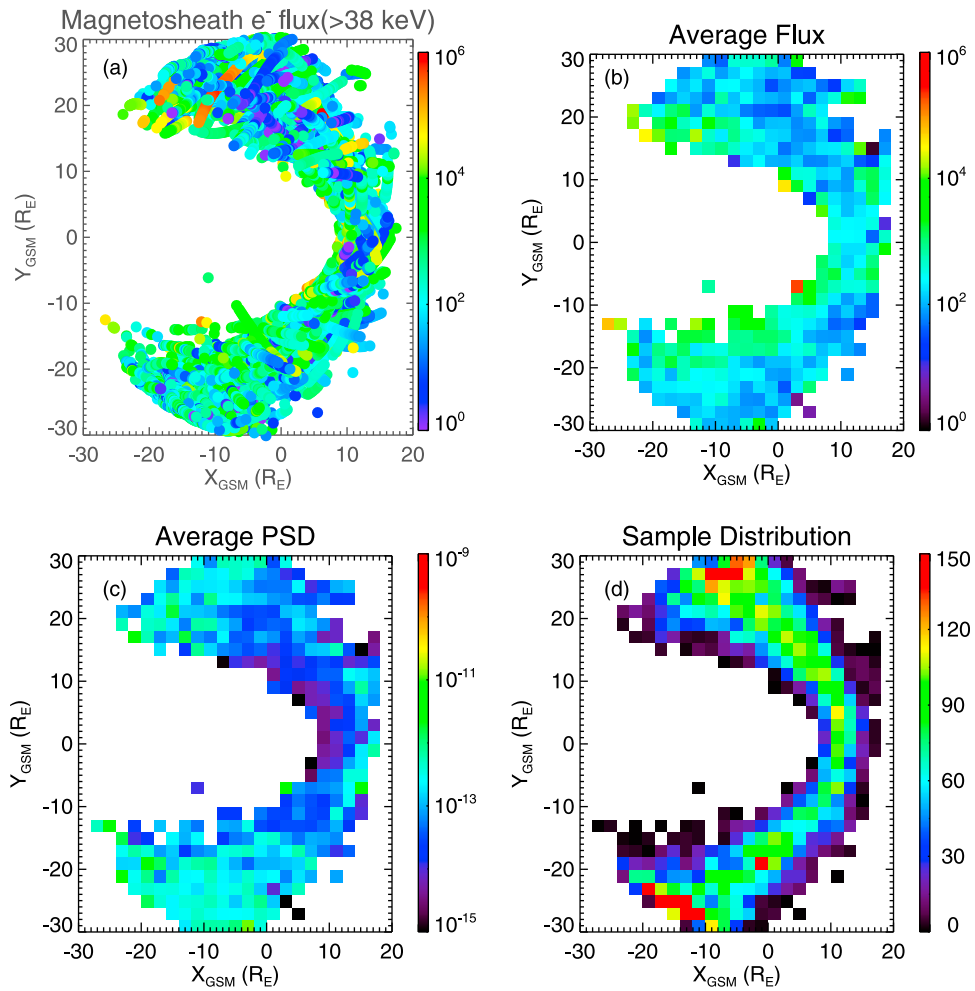

Figure 5. (a) The energetic electron fluxes in the magnetosheath measured by Geotail, with the positions of Geotail projected on the GSM XY plane. (b and c) The distribution of the energetic electron fluxes and PSDs (μ = 1000 MeV/G) averaged on a 2 × 2 R_E grid. (d) The spatial distribution of the data numbers.

which are possibly leaked from the magnetosphere can reach the bow shock.

6. Summary and Conclusions

[10] A comprehensive direct comparison of flux and phase space density (PSD) of energetic electrons in the magnetosheath and in the magnetosphere has been conducted and the results show that there are usually higher electron flux and PSD in the magnetosphere than in the magnetosheath, which suggests that energetic electrons in the magnetosheath cannot be a direct source sufficient for the energetic electrons in the magnetosphere through normal radial transport. Additional acceleration processes are required, mostly inside the magnetosphere, to produce the energetic electrons measured just inside the magnetopause. This is a significant finding and also another confirmation that the Earth's magnetosphere is an efficient accelerator of charged particles.

[11] Furthermore, our investigation of the flux distribution of energetic electrons inside the magnetosheath shows that there are two relatively high flux regions: one near the magnetopause and the other near the bow shock. Considering the higher energetic electron fluxes and PSDs in the magnetosphere than in the magnetosheath, the high energetic electron flux region in the magnetosheath near the magnetopause may be caused by the leakage of energetic electrons in the magnetosphere. The other high energetic electron flux region in the magnetosheath near the bow shock could be due to the energization of electrons in the solar wind while going through the bow shock. These two high-flux electron populations in the magnetosheath appear to rarely mix as shown by the lower flux in between, which may be due to the fact that they are all on open magnetic field lines, and thus are not easily transported from one region to the other.

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