

Butterfly Pitch Angle Distributions Observed by ISEE-1

by

Theodore A. Fritz^{a,*}, Mohamed Alothman^{a,b}, Jyotirmoyee Bhattacharjya^a, David L. Matthews^a, and
Jiasheng Chen^a

^aCenter for Space Physics, Boston University, 725 Commonwealth Ave., Boston, MA 02215

^bDepartment of Physics, University of Bahrain, P.O. Box 32038, Isa Town, Bahrain

*Corresponding Author: fax- 617-353-6463, e-mail- fritz@bu.edu

Abstract

The ISEE-1 satellite has observed butterfly pitch angle distributions (PAD) in protons and electrons from 20 keV to 2 MeV in the low latitude outer magnetosphere, which showed a sharp dropout in the flux of 90-degree pitch angle particles. These distributions were present on the night side near the magnetic equatorial plane and were far more prevalent in electrons than in protons. These distributions have been known for some time and have been associated with drift shell splitting in combination with either shadowing by the magnetopause or with a radial intensity gradient close to the Earth as equatorially mirroring particles drift around the Earth at radial distances from 6 to 12 R_E . In both a study of individual three-dimensional distributions and in a statistical survey, the occurrence of the butterfly PADs was found to have the following consistent behavior. (1) The anisotropy in the distributions increased with an increase in particle energy for both the protons and the electrons. (2) The anisotropy was less pronounced in the protons than in the electrons and usually disappeared altogether for the higher energy protons. (3) The radial location of the transition from and to the butterfly distribution was found to have a dependence on particle energy. (3a) The transition position occurred closer to the Earth with increasing particle energy for the butterfly PAD to normal PAD transition whereas (3b) the transition from the butterfly PAD to isotropic PAD occurred closer to the Earth with decreasing particle energy. In other words, the PADs were isotropic near the apogee of ISEE-1, peaked at 90° pitch angle close to the Earth, and butterfly over a range of radial distances, the width of which expanded in both directions with increasing energy. Modeling results are presented that are interpreted to demonstrate that the magnetopause and its motion are responsible for producing the butterfly PADs. The differences between ion and electron butterfly PADs are interpreted to indicate that the magnetopause has a layer of energetic particles that becomes a source of energetic particles to the inner magnetosphere and preferentially provides ions as close as the geostationary orbit routinely. These ions have a softer spectrum than the ions present at the same location on stably trapped drift trajectories (i.e., for those particles mirroring well away from the equator).

Introduction

An analysis followed by a statistical survey of "butterfly" distributions is reported here for both electrons and protons simultaneously from the ISEE-1 spacecraft. The distribution derives its name from the appearance of the particle flux vs. pitch angle plots in which a relative minimum exists for locally mirroring particles. Butterfly distributions could result from a couple of causes but we conclude for a number of reasons that they are caused by magnetopause shadowing. We address this assumption in the Discussion subsection "Modeling the Magnetic Field Conditions and Drift Paths" in some detail. This study has resulted not only in a better understanding of the morphologies of these two sets of butterfly distributions but has also provided some new insights regarding the physics of the magnetopause.

West (1965) made the earliest studies of butterfly distributions for electrons examining data from a Russian high-altitude nuclear detonation. Others have reported naturally occurring butterfly distributions (Serlemitsos, 1966; Pfitzer et al., 1969; Grannan et al., 1970; West et al., 1972, 1973; West and Buck, 1974; Luhman and Schulz, 1979). Haskell (1969) reported butterfly distributions for protons and electrons, though no attempt was made to distinguish between these two types of particles. Stevens et al. (1970) observed butterfly distributions for protons and Bogott and Mozer (1971) and Kaye et al. (1978) observed butterfly distributions for both electrons and protons. Later Garcia and Spjeldvik (1985) and Sibeck et al. (1987a) studied butterfly distributions for protons.

ISEE-1

The data set used is from the ISEE-1 spacecraft that was launched together with ISEE-2 on October 22, 1977 into an elliptic orbit with apogee of 23 R_E and perigee 280 km, a period of about 57 h and an inclination of about 28 degrees. A variable distance separated the two spacecraft, so data from complementary instruments can be used to separate space/time ambiguities. The Medium Energy Particles Experiment (MEPE) on ISEE-1 and -2 was designed to detect electrons and ions ranging from 22.5 keV to 1.2 MeV for electrons and 24 keV to 2 MeV for protons. These energy ranges were divided into eight energy channels each for electrons and ions in the standard Low Bit Rate [LBR] mode. The WAPS (Wide Angle Particle Spectrometer) on ISEE-1 was mounted on a scan

platform that rotated 160 degrees from almost parallel to almost anti-parallel to the spin axis in 12 satellite spin periods that required about 36.5 s. The sensor had a look direction opening conical half-angle of 5.3° . Williams et al., [1978] have given a detailed description of this instrument. The data returned from the ISEE-1 MEPE were converted to flux for each of the energy passbands and plotted as a function of both time and L-value [McIlwain, 1961] for the two years of operational life of the ISEE-1 experiment. Using simultaneous measurements of the geomagnetic field provided by the onboard magnetometer [Russell, 1978] the instantaneous pitch angle of a given particle measurement was determined. As illustrated in figure 1 for each 36.5 s spin/scan cycle of the WAPS a representative flux corresponding to each energy channel for eight sectors [LBR mode] of each spin was determined. This resulted in 96 samples being made on the 4π steradian unit sphere. The spin axis of ISEE-1 was perpendicular to the GSE X-Y plane. These fluxes could be displayed in a color coded manner on a mercator projection of the unit sphere where the vertical axis is the polar angle and the horizontal axis is the azimuthal angle in spacecraft coordinates which were essentially Geocentric Solar Ecliptic [GSE] coordinates. The scale on the horizontal axis [φ] has the sunward direction at 0° and the 180° direction is antisunward. For clarity it is emphasized that the look direction is the direction from which the energetic particles are coming. The vertical axis direction [θ] is the scan direction where $\theta = 0^\circ$ is antiparallel to the spacecraft spin axis viewing the south ecliptic pole and $\theta = 180^\circ$ is parallel to the spin axis viewing the north ecliptic pole. At $\theta = 90^\circ$, the 0° and 90° azimuthal directions represent essentially the GSE X- and Y-axes, respectively. The pitch angle associated with each flux measurement was determined instantaneously from the magnetometer data and used to place contours of constant pitch angle on these unit sphere angle/angle [θ, φ] displays.

Three-Dimensional Observations

ISEE-1 frequently traversed the nightside pseudo-trapping region and depending on the dipole tilt, the s/c observed butterfly PAD when it got very close to the geomagnetic equator. The location of the spacecraft with respect to the magnetic equator was determined by examining the ratio of the magnetic field at the spacecraft (denoted B) to that at the equator (minimum B denoted B_0), denoted B/B_0 . Figure 2 shows the ratio of the magnetic field at the spacecraft to that of the field line minimum (B/B_0 , solid line), the spacecraft radial distance ($R_{S/C}$, dash-dot line) and the radial

distance of the field line minimum (R_o , dashed line). The spacecraft coordinates were obtained from the Multi-Coordinate Ephemeris (MCE) with one-minute resolution and the magnetic field at the spacecraft was computed using IGRF and T96 [Tsyganenko and Stern, 1996] models. The field line going through the spacecraft was traced and the minimum was used to get the ratio. The modeled magnetic field at the spacecraft was used instead of the measured for consistency with B_o . At each location of the spacecraft, the field line was traced and R_o and B_o were calculated until the first open field line was reached as time increased to the right. The figure shows the values for the inbound leg of the orbit starting from April 9 (DoY 99) 11:00 UT to April 10 (DoY 100) 07:53 UT, 1978, with time increasing to the right. The vertical dashed lines mark the spacecraft distances of 6 and 11 R_E while the horizontal dotted line indicates a value of 1.3 for B/B_o . Here, a range for B/B_o of 1 to 1.3 was considered corresponding to equatorial pitch angle range of 90° to 61° . The discontinuities in the modeled values are mainly due to the discontinuities in the solar wind inputs and their one-hour resolution. ISEE-1 particle measurements are given in the "angle-angle" plot format discussed earlier.

Figure 3 shows ISEE-1 measurements during an inbound pass for the period from 03:40 to 05:40 UT in about 8.5-minute intervals of the E3 electron channel (75 to 120 keV). Time in the figure increases from left to right and continues on the second row and so on. These three dimensional data are plotted in the Mercator projection format of the unit sphere described in Figure 1. The vertical axis is the coordinate θ and the horizontal coordinate is ϕ as described above. The first panel at 03:40:34 UT shows a low isotropic flux. Contours of constant pitch angle determined by the instantaneously measured magnetic field show that the field was mainly radial in a tail-like configuration. The next panel shows an increase in the flux and the emergence of the butterfly PAD. Referring to the color bar on the left, more particle flux was seen parallel and anti-parallel to the field line compared to the perpendicular direction. Around 04:23:07 UT, a flux minimum associated with the bounce loss cone becomes apparent. The butterfly PAD persisted until about 05:05:40 UT where a "normal" distribution with a minimum around 0° and 180° and a maximum around 90° pitch angles was seen. Through this sequence the field can be seen changing from a mainly radial to a dipole-like (mainly vertical) orientation.

Figure 4 shows the measurements for the next higher electron energy channel E4 (120 to 189 keV) in the same format as Figure 3. Comparing this figure to the previous one sees two energy dependent features. The first is that the difference between the particle flux at 90° and 45° in the butterfly PAD is larger for the higher energy electrons, and the second is the location of the PAD transition from isotropic to butterfly and from butterfly to normal. For the isotropic to butterfly transition the radial distance is larger for the higher electron energy. For the butterfly to normal transition distance, the higher energy transition occurs at a smaller radial distance.

Figures 5 and 6 show the proton data in the same format as Figure 3 for the same portion of the orbit but from 04:06 to 05:40 UT in about 6.7-minute intervals. Figure 5 shows proton measurements for the P3 (65.3 to 95.5 keV) energy channel and Figure 6 for P4 (95.5 to 142 keV) channel. Both figures start with isotropic PAD, going to butterfly with a filled bounce loss cone, then butterfly with an empty loss cone, then a normal PAD with maximum around 90° . The two features seen with the electron PAD can be seen in a similar manner with the protons, i.e., the higher the energy the larger the difference between the flux at 90° and intermediate pitch angles and the variation in radial distance of the PAD transitions with energy. With the lower proton energy channel the drift loss cone started to fill up around 05:06:17 UT and a maximum around 90° or normal distribution was first seen around 05:19:39 UT. On the other hand, the fill up for the higher energy protons started around 05:19:39 UT and a maximum around 90° was seen around 05:33:01 UT. Garcia and Spjeldvik [1985] also noted this fact, (e.g., their figure 12).

This PAD transition behavior is more evident in Figure 7 that is part of the inbound leg of an ISEE-1 orbit on March 24, 1978. This orbital pass was recorded in High Bit Rate [HBR] mode in which the number of sectors and the number of energy channels are each doubled to 16. The four columns represent four different electron energy channels, E1, E5, E10, and E14 with energy responses as indicated, while the three rows represent three different locations along the orbit. The color bar is normalized to the maximum of each energy channel. The first row shows the butterfly PAD in all energy channels at $R_{S/C} = 8.1 R_E$. As the spacecraft moved inward, the PAD of the first energy channel showed a normal distribution, while the other three are showing the butterfly PAD at $R_{S/C} = 7.0 R_E$. The third row shows the lowest three channels at $R_{S/C} = 6.0 R_E$ with normal but

the highest still showing the butterfly PAD. Figure 8 shows the proton PAD in the same format as Figure 7 for the same orbit on March 24, 1978. The energy channels are given at the top of the figure with the first row showing PAD at $R_{S/C} = 8.1 R_E$, the second row at $R_{S/C} = 7.85 R_E$, and the third row at $R_{S/C} = 7.2 R_E$. An interesting observation is seen in the proton measurements given in Figure 8. The first row shows a butterfly PAD in all four of the energy channels. However, in the second row the observed butterfly PADs have an enhancement around 90° in the first energy and second channels. The enhancement at 90° in these two energy channels seemed to be superimposed on a butterfly PAD that was present in those as well as the higher energy channels. This observation has implications to later a discussion on a layer of energetic ions on the magnetopause serving as a source of particles for the inner magnetosphere. Comparing the fluxes around 90° and those around 45° (or 135°) a softer spectra is clearly evident for that population around 90° pitch angle compared to those with intermediate pitch angles. Examining the magnetospheric indices around the measurement time did not reveal any activity, as Dst was -7 nT, Kp was 1o, with nominal solar wind, IMF and AE conditions.

A Statistical Survey

In order to determine whether these observations are a general feature of the nightside magnetosphere a statistical survey was conducted. As noted earlier the data returned from the ISEE-1 MEPE were converted to flux for each of the energy passbands and plotted as a function of both time and L-value (McIlwain, 1961) for the two years of operational life of the ISEE-1 experiment. Using simultaneous measurements of the geomagnetic field provided by the on-board magnetometer (Russell, 1978) the instantaneous pitch angle of a given particle measurement was determined. For each 36.5 s spin/scan cycle of the WAPS a representative flux corresponding to both a local pitch angle of 90° and to 30° was selected and it was these fluxes that were plotted on the time-based and radial profile summary plots noted above. Rather than examine each 36.5 sec spin/scan cycle for the occurrence of the butterfly PAD it was readily possible to identify these PADs in the summary plots. The radial profile plots were examined for either one of two conditions: (1) a data selection condition based on whether the pitch-angle distribution was displaying a butterfly condition with the fluxes at pitch angles of 30° exceeding the fluxes at 90° and (2) an orbit selection condition based on whether the ISEE-1 satellite was close to the

geomagnetic equatorial plane determined by monitoring the B/B_0 parameter carried in the satellite ephemeris. Orbits close to the geomagnetic equatorial plane were chosen such that $B/B_0 < 5$ during some portion of the passage of the spacecraft through the $6 < L < 11$ region.

Figure 9 shows a plot similar to Figure 2 for the inbound portion of the ISEE-1 orbit on day 92 and 93 of 1978. Figures 10(a) and 10(b) show fluxes of 90° and 30° pitch angle electrons as a function of radial distance for each energy channel as indicated. The fluxes of 90° and 30° pitch angle protons are displayed in Figures 11(a) and 11(b). This is an example of an ISEE-1 pass that satisfied both the orbit and the data criteria of this study. For $L < 6$ the particle pitch angle distributions are normal, i.e. the flux of 90° pitch angle particles was greater than the flux of 30° pitch angle particles, but around $L=6$ the flux of 90° pitch angle particles suddenly dropped out. The dropout was progressively greater for higher energies. The particle distribution function became butterfly-shaped, i.e., it had a minimum for 90° pitch angle particles. The B/B_0 was approximately 1.1 during the period in which the butterfly distributions were seen. The electron butterfly distributions were observed in all electron energy channels and became more pronounced with increasing energy. The difference in the anisotropies of the electron and proton butterfly distributions is evident from figures 10 and 11. The dropout was less pronounced in the case of the protons than in the case of the electrons and was not present in all energy channels in the case of protons. It is interesting to note that for the lowest energy range there was a small enhancement of the flux of 90° pitch angle protons with respect to the flux at lower pitch angles at the same time that a butterfly distribution was observed for a similar energy range for electrons. These are similar to the results stated earlier from an analysis of the full three-dimensional proton distributions on March 24, 1978, but determined here from the radial profiles of the particle fluxes at the two pitch angles.

The butterfly pitch angle distributions were identified in each of the orbits during the rotation of the apogee of the ISEE spacecraft through all local times over the two years of 1977-1979. The location of their occurrence was tabulated according to local time, L shell, and B/B_0 using summary radial profile plots of the ISEE-1 data similar to those in figures 10 and 11. Figure 12 shows the distribution of the electron and proton butterfly PADs in local time. The butterfly PADs observed

have been binned into six local time sectors, 00-04h, 04-08h, 08-12h, 12-16h, 16-20h, and 20-00h, based on the data selection criteria requiring B/B_0 to be less than 5. The number of orbital passes was used to normalize the number of occurrences of the butterfly PADs in any given local time interval to obtain a frequency of occurrence. It can be seen that butterfly PADs in the electrons were found to occur on a majority of the passes in the sectors from 16h through midnight to 04h. The butterfly PADs were found to extend into the dayside near dusk but there were no butterfly observations in the post-dawn/pre-noon sector. The electron butterfly belt was found to extend from pre-dusk to dawn within an L shell range of about 6 to 12. The butterfly distributions were consistently observed when the B/B_0 parameter was between 1.0 and 1.3 but on rare occasions they were observed at B/B_0 values up to 4. The inner boundary of the butterfly PADs varied in L shell between about 6 and 7.5 throughout this entire belt. The pitch angle anisotropy for these PADs was found to be progressively enhanced with increasing energies (as can be seen from the April 3, 1978 event). The difference in frequency of occurrence of butterfly PADs between the dawn and dusk sectors is to be expected for the interpretation that magnetopause shadowing produces the butterfly PAD since the electrons drifting eastward should encounter the pre-noon magnetopause and consequently the post-noon outer magnetosphere is expected to show more butterfly distributions. This is similar to previous studies [e.g., West et al., 1973].

Butterfly distributions in the case of the protons were found to occur outside $L=6$ and the PAD was generally normal within $L=6$. Butterfly PADs in the protons were observed about 36% of the time that the electron butterfly PADs occurred. The butterfly belt was found to extend in L shell between about 6 and 10.5. The highest percentage occurrence was found around dawn. No butterfly PAD was observed for the protons in the interval around dusk. The higher concentration of proton butterfly PADs in the post-midnight sector is in accordance with interpretation of magnetopause shadowing since the protons reach the magnetopause drifting westward. Previous studies [e.g. Sibeck et al. (1987b)] also showed similar local time dependence but provided a different interpretation of their cause. The inner edge of the butterfly belt varied between L values of 5.8 and 8. The pitch angle anisotropy increased with an increase in energy of the proton but not as strongly as that shown by the electrons and the anisotropy appeared to disappear at the highest energies sampled.

A summary of the results of the statistical survey from the proton and electron data reveal the following facts that have been recorded in previous studies and are confirmed by this study:

- (a) There was a dawn-dusk asymmetry in the butterfly distributions of both the protons and the electrons, the electrons having a higher concentration near dusk and the protons having a higher concentration near dawn.
- (b) The butterfly belt was observed in the outer magnetosphere between L values of 6 and 12 for both the protons and the electrons and the inner edge of the distribution varied in L shell between 5.8 and 8.
- (c) The anisotropy in the distribution was found to increase with an increase in particle energy for both the protons and the electrons but was greater for the electrons. The anisotropy at the largest proton energies was not present.
- (d) The radial location of the transition from the normal PAD to a butterfly PAD was dependent on particle energy with this transition position occurring slightly closer to the Earth with increasing particle energy.

There were three interesting observations made in the present study, which lead to some questions if magnetopause shadowing was their cause:

- (a) The butterfly PADs were more frequent in the electrons than in the protons over the entire nightside, proton butterfly PADs being observed only about 36% of the time that those in the electrons were observed. The electron butterfly PADs were observed most of the time that ISEE was within about 15 degrees of the geomagnetic equator.
- (b) When the butterfly distributions were observed in both the electrons and the protons they were observed in fewer channels in the protons than in the electrons. In some cases enhancement of the 90° pitch angle flux was seen in the protons instead of a dropout. The P1 channel shown in figure 11a is an example of this as well as in figure 8.
- (c) The pitch angle anisotropy observed for the butterfly distributions was generally greater in the case of the electrons than in the case of the protons, i.e., the dropout in the flux of 90° pitch angle particles with respect to the 30° pitch angle particles is greater in the case of the electrons than in the case of the protons.

The Kp and Dst geomagnetic indices for the observed butterfly distributions were noted in order to get an overview of the overall magnetospheric activity for the periods during which these events occurred. Kp was greater than 4- in about 10% of the cases, the Kp was between 3 and 3+ for 6% of the events and in the rest of the cases Kp was less than 3. The Dst was between -60 and -40nT in 10% of the cases and between -40 and -30nT for 6% of the cases. The remaining cases had Dst greater than -30nT. Thus the magnetosphere seemed to be mostly quiet or of average activity during most of the observations.

Discussion

Modeling the Magnetic Field Conditions and Drift Paths

Different causes for the occurrence of butterfly distributions have been suggested in the literature. Apart from magnetopause shadowing, (West et al., 1972, 1973; Sibeck et al., 1987a,b; Wilken et al., 1986), differential drift speeds of particles with different pitch angles (Konradi et al., 1973; Solomon, 1976; Luhmann, 1977), electric field drift shell splitting (Korth et al., 1983), radial flux gradients (Pfitzer et al., 1969; Garcia and Spjeldvik, 1985; Sibeck et al., 1987b) are also suggested mechanisms. In the current work we have studied butterfly distributions that were found to occur outside L=6 routinely. We have assumed that the butterfly distributions discussed in this paper were produced by a combined action of magnetopause shadowing and drift shell splitting. It is possible that drift shell splitting in combination with a radial gradient in the intensity profile can also produce butterfly distributions as described by Pfitzer et al. (1969) and Sibeck et al. (1987a). Of the various other mechanisms suggested we can rule out those that rely on a time variation since these mechanisms can maintain a butterfly distribution only for a limited time. In an analysis of electron butterfly distributions observed by the Polar energetic particle detectors (Duguay and Fritz, 2002), it was shown that the occurrence of butterfly distributions had a consistent onset near 6 R_E at the nightside equatorial plane. Polar, unlike ISEE-1 will always cross the magnetic equator. These distributions were not observed by Polar in 1996, 1997, and 1998 but began to be observed in 1999 near midnight. This was due to the orbital precession of the line of apsides of the Polar orbit toward the equatorial plane. As the outbound crossing of the equator by Polar moved beyond 6 R_E these distributions were observed and as time has passed they have been observed at both earlier and later local times away from midnight with their onset at a greater radial distance than 6 R_E . In

2001 they were observed at dawn and dusk and as data from 2002 have been analyzed these distributions are being observed sunward of the terminator in an increasingly broad section of local time. The equatorial position of the onset is consistent with a constant B contour that maps close to the dayside magnetopause and therefore is consistent with the proposition that these butterfly distributions were produced by magnetopause shadowing coupled with the drift shell splitting. If these distributions were produced by drift shell splitting coupled with a dayside negative radial gradient (Pfitzer et al., 1969; Sibeck et al., 1987a) they should be observed well inside $6 R_E$ at midnight and without a particular onset at any given radial distance. In fact they should not be observed much beyond $6 R_E$ around midnight for such a mechanism operating without magnetopause shadowing. Observationally this is not the case. As an additional point an analysis of a storm sudden commencement (SSC) and its resultant effect on the energetic particle pitch angle distributions measured by the CRRES satellite was done by R. Stadsnes (1997). Stadsnes demonstrated that the timing of the onset of butterfly distributions as a function of energy observed in energetic ions was consistent with shadowing by a compressed subsolar magnetopause and subsequent drift to the nightside position of CRRES.

The magnetopause has been shown to be in nearly constant motion (e.g., Fritz and Fahrnensteil, 1982). It has a nominal subsolar position of $9-10 R_E$ but has been frequently observed inside the geostationary orbit. This motion of the magnetopause has been routinely measured to be as high as 100 km/s . The motion of this boundary is the important parameter in determining how particles are lost as they drift through the subsolar region. The magnetic field minimum does not lie on the magnetic equatorial plane but rather bifurcates on the dayside and moves to latitudes associated with the cusps (Shabansky, 1971). Delcourt and Sauvaud (1999) have modeled the drift of particles from the nightside using an older data-based model of Mead and Fairfield (1975). They have shown that only a narrow range of radial distances at local midnight would be affected by this move up to cusp latitudes. A particle started at $7 R_E$ on the magnetic equator at midnight will drift completely around in local time remaining at the equator whereas one started at $9 R_E$ will encounter the magnetopause and be lost. Only at $8 R_E$ did Delcourt and Sauvaud (1999) find that the particle would move into and through the high latitude minimum where their work showed that the particle becomes lost out of the magnetosphere. Since the motion of the magnetopause is \sim one R_E/min , the

distinction of where the particle impacts the magnetopause along its drift trajectory becomes lost to any modeling effort that relies on a static magnetic field.

Stadsnes (1997) demonstrated additional features of the motion of the magnetopause that impact the drift of the particles through the subsolar region. With the subsolar magnetopause at $8 R_E$ rather than $9 R_E$ the particles will drift further out at local noon. He illustrated this with a particle of 100 keV drifting along the $B_0=100$ nT contour. Starting near the geostationary orbit at midnight the particle will drift to $7.7 R_E$ at noon when the subsolar magnetopause is at $9R_E$ but it will drift out to $8.1 R_E$ and be lost to the magnetosheath when the magnetopause is at $8R_E$. Stadsnes (1997) further demonstrated the drastic impact that such a compression will have on the drift speed of the particles near local noon due to the reduction of the magnetic field gradient resulting from the compression of the magnetopause by the solar wind. In the model by Roederer (1970) that Stadsnes used, the drift time around the Earth for a 100 keV particle along the $B_0=100$ nT contour changes from 100 minutes to 265 minutes when the magnetopause position changes from $9 R_E$ to $8 R_E$. The difference in time means that the particle drifts very slowly through local noon. The increased time spent in this region increases the probability that the particle will be lost to the magnetosheath by the continual motion of the magnetopause.

As a means of an initial check, to confirm the fact that these distributions are indeed caused by magnetopause shadowing, the magnetic field at the spacecraft was noted at the inner edge of the butterfly distribution and then the magnetic field at the nose of the magnetopause was calculated by balancing the solar wind pressure against the magnetospheric pressure. A nose magnetic field less than or equal to the magnetic field at the spacecraft implied that the locally mirroring particles were on drift paths that reach the vicinity of the magnetopause during their azimuthal drift around the earth.

Once all the data had been tabulated in the present study, a more precise check was made using the T96 external field model (Tsyganenko (1995)). The reason for using T96 was that it included a realistic magnetopause. For a particular UT and solar wind condition, field lines were traced in the GSM coordinate system and the minimum value of B on these field lines was found. The contours

of B_0 were traced on the equatorial plane from this calculation. The contours were of a similar nature to the Fairfield model (Fairfield, 1971), the advantage of the present work being that the contours can be traced at a particular time, using the parameters of the moment whereas the previous model gives the average contours for the magnetosphere. The magnetopause being constantly variable, this gives us a better prediction capability. Knowing that energetic particles with a 90° pitch angle at the equatorial plane follow drift paths of constant B field magnitude, these contours then are also the drift paths for these particles. Figure 13 shows the contours for the ISEE-1 pass on day 92/93 shown in Figures 9-11. It can be easily seen, that, as would be expected, the contours are further out on the dayside than they are on the nightside; thus the contour in the vicinity of the magnetopause around noon maps to an L shell value of about 6 at midnight.

A question that usually arises in the drift of energetic particles is the possible role of a dawn-to-dusk electric field associated with convection in the magnetosphere. The presence of a dawn-to-dusk convection electric field with associated potential Φ has the possibility to affect the particle drift trajectories in an energy dependent manner. The quantity $\mu B + q\Phi$, associated with the total particle energy, will remain conserved where μ is the magnetic moment of the particle and q is its charge state. This has the effect of displacing the lower energy drift trajectories toward the Earth at dawn and away from Earth at dusk compared to contours of constant B in essentially the manner ascribed to the bulge of the plasmasphere. Kosik (1979) studied the behavior of electrons with energies greater than 40 keV at the geostationary orbit. His main conclusion is that the drift trajectories will be displaced in the manner just described. Kosik concluded after examining particle data taken by a geostationary satellite that "It was not possible to discern any electric field effects on low energy particles." The presence of such electric field drift effects will reverse the energy dependence of the radial gradient at dawn and dusk and have little effect at midnight on any energy dependent gradient. We have found that the energy dependence of the transition to the butterfly distribution from or to normal and isotropic distributions is the same, independent of local time. Kosik (1979) concluded also that for a fixed radial distance (e.g., 6.6. RE) the intensity of equatorially mirroring electrons will peak in the post-noon/dusk sector with the presence of a dawn-to-dusk electric field when compared to predicted intensities in the absence of such an electric field. In Figure 12 of the paper this sector is where the peak frequency of occurrence of the electron

butterfly PAD occurs which requires a minimum in the equatorially mirroring electron fluxes. This argues against the role of any dawn-to-dusk electric field affecting the results presented in the paper. We therefore believe that effects of a dawn-to-dusk electric field are not important for the results reported in our paper.

The Magnetopause As A Source For Energetic Particles

The process of magnetopause shadowing due to the drift shell splitting caused by the difference in pitch angles of drifting particles is expected to be an energy independent process, i.e., the particles in different energy channels should show the same drift patterns based on their pitch angles. We would then expect the dropouts in the flux of 90° pitch angle particles in the different energy channels of the protons and the electrons to be the same. But this is contrary to observation. The butterfly distributions are found to be less anisotropic in the lower energy channels than in the higher energy channels. Also for the same butterfly event the protons are found to be less anisotropic than the electrons. In the lowest energy proton channel (24 keV to 44 keV) for day 93, for example (Figure 11), there is an enhancement in the 90° pitch angle particle flux with respect to the flux at 30° pitch angle. It thus seems apparent that there is a source of particles that is filling up the void that produces the butterfly distributions. This is the interpretation drawn from figure 8 as well. Until now the magnetopause has generally been regarded as a sink for particles, both electrons and ions. This fact is also borne out by the observations of butterfly distributions in the protons and the electrons, with the proton butterfly PAD showing a greater concentration in the post-midnight sector and electron butterfly PAD in the pre-midnight sector. This is expected from the drift directions of energetic protons and electrons in the magnetosphere. But in the case of the protons the dropout in the 90° pitch angle particle flux is far less drastic than that for electrons in the same energy range. This leads us to consider the possibility of the magnetopause acting not just as a sink of energetic particles, but a layer of such particles on the magnetopause can act as a source. From the observations it appears to be a preferential source for protons of a given energy greater than 24 keV when compared to electrons of the same energy.

The characteristics of the source observed from our medium energy particle data can be summarized as follows:

- (1) As corroborated by the modeling study the source must be present near the magnetopause for particles on open drift paths (i.e., an equatorial pitch angle near 90°) which are lost from the magnetosphere in a fraction of their azimuthal drift period.
- (2) The source is preferentially active for the protons, since the pitch angle anisotropy is observed to be greater for the electron butterfly distributions.
- (3) The source is an energy dependent one and more active in the lower energies, leading to the butterfly distributions being more filled up in the lower energy proton channels than in the higher energy ones.
- (4) The ion source energy spectrum from 20 keV to a few hundred keV is noticeably softer than that of the lower pitch angle particles in the same energy range.
- (5) The source is probably a time-dependent one though the exact nature of its time dependence is not clear yet.

The possibility of the magnetopause source has been given some consideration in theory. Tverskoy (1970) considered the magnetic drift along the normal to the magnetopause due to tangential field gradients, with protons entering in the morning sector via their gradient drift. This is in agreement with our observations of partially filled up proton butterfly PAD in the post-midnight outer magnetosphere. Newell and Meng (1997) considered a model for the diffusion of sheath plasma onto closed field lines, since observational evidence existed for the LLBL on both open and closed field lines. Antonova (1996) suggested that the leakage of particles trapped in the cusp due to the local field minimum existing on open field lines adjacent to the magnetopause is a possible mechanism during both quiet and disturbed times. This would lead to the formation of an energetic particle layer at the magnetospheric boundary, as the cusp is topologically related to the entire magnetopause. Chen et al. (1997, 1998) have reported the existence of a probable acceleration region for energetic ions associated within the high altitude cusp using data from the Polar satellite. Fritz and Chen (1999) have discussed the role of such a source of energetic particles in determining and controlling the dynamics and variability of the inner magnetosphere. It is possible that the partial or total filling up of proton butterfly distributions that we observe with the ISEE data is a consequence of these particles entering the magnetosphere on open drift paths on the dawn side.

Acknowledgement

The authors wish to thank Erik Beiser, Jeremy Coombs, Ryan Duguay, and Gina Gugliotti, all of Boston University for their contributions in the preparation of this manuscript. The useful comments of the reviewers are also gratefully acknowledged.

References

- Antonova, A. E., 1996, High-latitude particle traps and related phenomena, *Radiation Measurements*, **26**, 409-411.
- Bogott, F. H. and Mozer, F. S., 1971, Equatorial electron angular distributions in the loss cone and at large angles, *J. Geophys. Res.*, **76**, 6790-6805.
- Chen, Jiasheng, Fritz, T. A., Sheldon, R. B., Spence, H. E., Spjeldvik, W. N., Fennell, J. F., Livi, S., 1997, A new, temporarily confined population in the polar cap during the August 27, 1996 geomagnetic field distortion period, *Geophys. Res. Lett.*, **24** (12), 1447-1450.
- Chen, Jiasheng, Fritz, Theodore A., Sheldon, Robert B., Spence, Harlan E., Spjeldvik, Walther N., Fennell, Joseph F., Livi, Stefano, Russell, Christopher T., Pickett, Jolene S. and Gurnett, Donald A., 1998, Cusp energetic particle events: Implications for a major acceleration region of the magnetosphere, *J. Geophys. Res.*, **103** (No.A1), 69-78.
- Delcourt, D.C. and Sauvard, J. –A., 1999, Populating of the cusp and boundary layers by energetic (hundreds of keV) equatorial particles, *J. Geophys. Res.*, **104**, No. A10, 22635-22648.
- Duguay, R. T. and Fritz, T. A., 2002, A statistical study of electron butterfly pitch angle distributions using POLAR (abstract), *Eos Trans. AGU*, **83**, (19), Spring Meet. Suppl., Abstract SM42A-14.
- Fairfield, D. H., 1971, Average and unusual locations of the earth's magnetopause and bowshock, *J. Geophys. Res.*, **76**, 6700-6716.
- Fritz, T.A., and Fahrenstiel, S.C., 1982, High temporal resolution energetic particle soundings of the magnetopause on November 8, 1977 using ISEE-2, *J. Geophys. Res.*, **87** (No.A4), 2125-2131.
- Fritz, T. A. and Chen, J., 1999, The cusp as a source of magnetospheric particles in Proceeding of the Workshop on "Space Radiation Environment Modeling: New Phenomena and Approaches" which was held in Moscow, Russia on October 7-9,1997 published in *Radiation Measurements*, **30** No. 5, 599-608.
- Garcia, H. A. and Spjeldvik, W. N., 1985, Anisotropy characteristics of geomagnetically trapped ions, *J. Geophys. Res.*, **90**, 347-358.
- Grannan, R., White, R. S., and Stephens, J. R., 1970, Electron drift in the earth's magnetic field (abstract), *Eos Trans. AGU*, **51**, 806.

- Haskell, G. P., 1969, Anisotropic fluxes of energetic particles in the outer magnetosphere, *J. Geophys. Res.*, **74**, 1740-1748.
- Kaye, S. M., Lin, C. S., Parks, G.K. and Winckler, J. R., 1978, Adiabatic modulation of equatorial pitch angle anisotropy, *J. Geophys. Res.*, **83**, 2675-2682.
- Konradi, A., Williams, D. J., and Fritz, T. A., 1973, Energy spectra and pitch angle distributions of storm-time and substorm injected protons, *J. Geophys. Res.*, **78**, 4739-4744.
- Korth, A., Kremser, G., Roux, A., Perraut, S., Sauvaud, J. A., Bosqued, J. M., Pedersen, A. and Aparicio, B., 1983, Drift boundaries and ULF wave generation near noon at geostationary orbit, *Geophys. Res. Lett.*, **10**, 639-642.
- Kosik, J. C., 1979, Influence of electric fields on charged particle motion and electron fluxes at synchronous altitudes, in *Quantitative Modeling of Magnetospheric Processes*, edited by W. P. Olson, pp. 569–581, AGU Monogr. 21.
- Luhman, J.G., and Schulz, M., 1979, Magnetic shell tracing: A simplified approach, in *Quantitative Modeling of Magnetospheric Processes*, edited by W. P. Olson, pp. 582–591, AGU Monogr. 21.
- Luhman, J. G., 1977, The effect of transient localized sources on equatorial pitch angle distributions in the magnetosphere, *J. Geophys. Res.*, **82**, 1943-1946.
- McIlwain, C.E., 1961, Coordinates for mapping the distribution of magnetically trapped particles, *J. Geophys. Res.*, **66**, 3681-3691.
- Mead, G. D., and Fairfield, D. H., 1975, A quantitative magnetosphere model derived from spacecraft magnetometer data, *J. Geophys. Res.*, **80**, 523-542.
- Newell, P. T. and C-I. Meng, 1997, Open and closed low latitude boundary layer, The Johns Hopkins University Applied Physics Laboratory, preprint, SRA-97-07.
- Pfizer, K., Lezniak, T. W. and Winckler, J. R., 1969, Experimental verification of drift shell splitting in the distorted magnetosphere, *J. Geophys. Res.*, **74**, 4687-4693.
- Roederer, J. G., 1967, On the adiabatic motion of energetic particles in a model magnetosphere, *J. Geophys. Res.*, **72**, 981-992.
- Russell, C. T., 1978, The ISEE1 and 2 fluxgate magnetometers, *IEEE Trans. Geosci. Electr.*, **GE-16**, 239-242.

- Serlemitsos, P., 1966, Low energy electrons in the dark magnetosphere, *J. Geophys. Res.*, **71**, 61-77.
- Shabansky, V. P., 1971, Some process in the magnetosphere, *Space Sci. Rev.*, **12**, 299-418.
- Sibeck, D. G., McEntire, R. W., Lui, A. T. Y., and Krimigis, S. M., 1987a, A statistical study of ion pitch angle distributions, in *Magnetotail Physics*, edited by A. T. Y. Lui, 225-230, Johns Hopkins Press, Baltimore, Md.
- Sibeck, D. G., Lui, A. T. Y., Lopez, R. E. and Krimigis, S. M., 1987b, Magnetic field drift shell splitting: cause of unusual dayside particle pitch angle distributions during storms and substorms, *J. Geophys. Res.*, **92**, 13,485-13,497.
- Solomon, J., 1976, On the azimuthal drift of substorm-injected protons, *J. Geophys. Res.*, **81**, 3452-3454.
- Stadsnes, R., 1997, Dynamics of a magnetospheric substorm, PhD thesis, University of Bergen, Dept. of Physics, Bergen, Norway.
- Stevens, J. R., Martina, E. F., and White, R. S., 1970, Proton energy distributions from 0.060 to 3.3 MeV at 6.6 earth radii, *J. Geophys. Res.*, **75**, 5373-5385.
- Tsyganenko, N. A., 1995, Modeling the earth's magnetospheric magnetic field confined within a realistic magnetopause, *J. Geophys. Res.*, **100**, 5599-5612.
- Tverskoy, B. A., 1970, Electric fields in the magnetosphere and the origin of trapped radiation, *Solar Terrestrial Physics*, Dyer(ed.), 297-317, D. Reidel, Dordrecht.
- West, H. I., Jr., 1965, Some observations of the trapped electrons produced by Russian high altitude nuclear detonation of October 28, 1962, *Radiation Trapped in the Earth's Magnetic Field*, edited by B. M. McCormac, 634-662, D. Reidel, Dordrecht.
- West, H. I., Jr., Buck, R. M., and Walton, J. R., 1972, Observation of the shadowing of electron azimuthal-drift motions near the noon magnetopause, *Nature*, **240**, 6.
- West, H. I., Jr., Buck, R. M., and Walton, J. R., 1973, Electron pitch angle distributions of energetic electrons throughout the magnetosphere as observed on OGO 5, *J. Geophys. Res.*, **78**, 1064-1081.
- West, H. I., Jr. and Buck, R. M., 1974, Pitch angle distributions of energetic electrons in the equatorial regions of the outer magnetosphere: OGO 5 observations, *Magnetospheric Physics*, edited by B. M. McCormac, 93-104, D.Reidel, Hingham, MA.

Wilken, B., Baker, D. N., Higbie, P. R., Fritz, T. A., Olson, W. P., and Pfizter, K. P., 1986, Magnetospheric configuration and energetic particle effects associated with a SSC: A case study of the CDAW 6 event on March 22, 1979, *J. Geophys. Res.*, **91**, 1459-1473.

Williams, D. J., Keppler, E., Fritz, T. A., Wilken, B., and Wibberenz, G. W., 1978, The ISEE-1 and 2 medium energy particles experiment, *IEEE Trans. Geosci. Electr.*, **GE-16**, 270-278.

Figure Captions

Fig. 1. (a) The unit sphere is produced during one 36.5 sec spin/scan cycle of the WAPS instrument onboard ISEE1. The unit sphere can be made into (b) a mercator projection, on which pitch angle contours and flux intensities are overlaid. The resulting plot is a Pitch Angle Distribution (PAD).

Fig. 2. Values of ISEE-1 radial distance, R_{SC} , the ratio of the modeled field at the spacecraft to that of the field line minimum, B/B_0 and the geocentric distance of the field minimum, R_0 . The values are for the inbound pass on April 9, 11:00 UT to April 10 08:00 UT (DoY 99 to 100) 1978.

Fig. 3. ISEE-1 75 to 120 keV electron (E3) for April 10 (DoY 100), 1978 from 03:40 to 05:40 UT in the format of Figure 1b. This is a mercator projection of the three dimensional unit sphere in essentially GSE coordinates where $\theta = 90^\circ$ is the GSE X-Y plane. The figure shows the transition of particles PAD from isotropic to butterfly to normal and the magnetic field from radial to a dipole-like configuration.

Fig. 4. Similar to figure 3 except for the electron energy of 120-189 keV (E4). Notice the deeper minimum and the location of the PAD transitions.

Fig. 5. Similar to figure 3 except for the proton energy of 44.5 to 54.8 keV (P3). Notice the shallower difference between the 45° and 90° fluxes and the location of the PAD transitions when compared to the electrons.

Fig. 6. Similar to figure 5 except for the proton energy of 54.8 to 65.3 keV (P4). Notice the location of the PAD transition.

Fig. 7. ISEE-1 observed electron PAD at different location and for different energies as indicated during the inbound ISEE-1 orbit on March 24 (DoY 83), 1978. This figure illustrates the different

locations of the PAD transition depending on the energy. The color bar scale is normalized to the maximum of each energy channel.

Fig. 8. ISEE-1 observed proton PAD at different location and for different energies as indicated during March 24 (DoY 83), 1978. This figure shows enhancements in the two proton lower energy channels and by comparing the flux intensity around 90° and 45° a softer spectra can be seen around 90° pitch angle. The color bar scale is normalized to a maximum of each energy channel that is not shown.

Fig. 9. The variation of the ratio of the magnetic field at the spacecraft to the minimum value of the magnetic field along the field line evaluated at each point along the spacecraft orbit. The spacecraft is moving inbound in this part of the orbit. $R_{s/c}$ (R_E) and R_o (R_E) indicate the location of the spacecraft and the B field minimum. B/B_o varies between 1 and 2 in the 6.0 to 14.0 R_E range.

Fig. 10(a) and (b). Butterfly distributions observed on 78/092 and 78/093 in a radial distance range between 6.0 and 11.0 R_E in the eight electron energy channels. A steep anisotropy is observed, with the flux at 90° pitch angle dropping below that at lower pitch angles (the flux at 30° is shown in the figures). The anisotropy becomes larger with an increase in particle energy from E1 to E8.

Fig. 11(a) and (b). Particle distributions observed on 78/092 and 78/093 in a radial distance range between 6.0 and 12.0 R_E in eight proton energy channels in the 30° and 90° pitch angle bins. The observed anisotropy is much less than that in the case of the electrons.

Fig. 12. Frequency of occurrence of butterfly distributions in electrons and protons (indicated as e^- and p^+) in the six local time sectors normalized to the number of spacecraft entries (indicated as s/c) in that sector. All spacecraft entries shown lie in the selected parameter range of $6.0 < R < 14.0$ and $1.0 < B/B_o < 5.0$. The frequency of occurrence is derived by normalizing the number of butterfly PAD observed for electrons and for protons with the number of s/c orbits that satisfy the selection criteria. The electron butterfly distributions show a more frequent occurrence than the proton butterfly distributions in almost all the local time sectors.

Fig. 13. Contours of minimum B field projected onto the GSM x-y plane. These are essentially the drift paths of energetic particles that mirror equatorially. The Tsyganenko (T96) model is used to calculate the contours of minimum magnetic field for four different times (78/092 23:00 UT, 78/093 00:00 UT, 01:00 UT and 02:00 UT). The three latter contours overlap each other. The spacecraft positions at the four times are indicated by ‘*’s. The butterfly distributions are observed up to the 02:00 UT when the spacecraft enters a region of closed drift paths.