Sources and sinks of equatorially mirroring energetic charged particles in the earth’s inner magnetosphere

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Abstract

The Imaging Proton Spectrometer (IPS) and the Imaging Electron Spectrometer (IES) on the Polar satellite have measured temporary deviations in the isotropy of the pitch angle distributions (PADs) of charged particles in the inner magnetosphere. As Polar passes through the nightside equatorial region, the IPS and IES observe dropouts of charged particles with pitch angles near 90°, known as butterfly distributions caused by the shadowing of the magnetopause. Additionally, Polar observes a lower energy (< 60 keV) injection of locally mirroring ions while simultaneously detecting butterfly PADs in both higher energy ions and electrons. With these observations and the modeling of single particle motion, it can be shown that the magnetopause may act as both a source and a sink for energetic ions within the earth’s magnetosphere.

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1 Introduction

The butterfly pitch angle distribution (PAD) was first described by West (1966) with observations of Soviet nuclear testing in the upper atmosphere on 28 October 1962. These PADs are characterized by a decrease in the flux of particles with pitch angles near 90°. This minimum, along with the additional field-aligned minima created by the loss cone, will form a butterfly shaped distribution. Later reports of naturally occurring butterfly PADs in populations of both electrons and protons were made by Serlemitsos (1966), Pfitzer et al. (1969), Bogott and Mozer (1971), West et al. (1973), West and Buck (1974), Kaye et al. (1978), and Fritz et al. (2003) among others.

Using the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) instrument package on the Polar satellite (Blake et al., 1995), the characteristics of the PADs of energetic ions and electrons are compared for two specific events. The butterfly shaped PAD, indicating a deficiency of locally mirroring charged particles are commonly observed as Polar passes through the equatorial region of the inner magnetosphere. The orbital dynamics of the satellite have allowed for the observation of a large portion of the radiation belt region. Many mechanisms have been proposed as the cause of the butterfly PAD, and through the modeling of ions and electrons, it can be supported that shadowing by the magnetopause can be at least one of the methods by which both 90° pitch angle electrons and ions are lost from the equatorial zone, and as reported herein, the magnetopause is a source for ions of lower energy (< 60 keV) as well.

The compression of the earth’s magnetic field due to contact with the solar wind leads to asymmetries in the geometry of the geomagnetic field with a dependence upon magnetic local time. For a given latitude and radial distance, the dayside magnetopause, having been compressed by the dynamic pressure of the solar wind has higher field strengths than the less disturbed nightside magnetosphere at a given radial distance. This deviation from a perfect magnetic dipole forces charged particles to drift in non-circular drift-paths. For equatorially mirroring particles, the conservation of the first adiabatic invariant will constrain these particles to paths of constant magnetic field strength. Consequently, particles will move radially outward as they drift from the nightside to dayside. Closer toward the earth, electrons and protons can remain stably trapped, as the dayside extension is not great enough to allow the particles to contact the magnetopause. Outside of this region, the drift paths may extend enough to allow these pseudo-trapped or quasi-trapped particles to scatter on the magnetopause. (Roederer, 1967, 1970)

The limit of stable trapping exists in the region of the nightside tail that is being studied. Polar observes butterfly distributions both well inside and well outside this boundary. Outside of the surface that is created by the boundary of stable trapping, electrons and ions exist with a specific pitch angle in which the drift paths will no longer be closed around the earth, but extend into the magnetopause and will be subject to scattering processes that will scatter the particles away from their initial drift shell (Roederer, 1970). In this region of quasi-trapping, charged particles with pitch angles near 90° cannot orbit the earth in stable drift paths, but more field-aligned particles, which
are not as affected by drift shell splitting, may remain in stable drift paths. It can be shown through particle modeling that the outer regions of Polar’s observations of the nightside equatorial plane are subject to the differential drift paths created in the quasi-trapping region.

2 Instrumentation

Energetic ion detection onboard the Polar spacecraft is completed through the Imaging Proton Spectrometer (IPS). The instrument consists of nine sensors that rotate azimuthally with the spin axis of the satellite. In total, the instrument can detect ions with a $180^\circ$ polar $\times \sim 12^\circ$ azimuthal field of view. In a 96 second integrated observation, IPS detects a full sky image at sixteen different energy bands with central energies ranging from 15.6 keV up to 1.51 MeV. The magnetic field direction, as measured onboard the Polar satellite (Russell et al., 1995), can then be used to determine the pitch angles of the protons detected by IPS. In a similar manner, the Imaging Electron Spectrometer (IES) can detect electrons with energies ranging from 20 keV to 400 keV, with a $180^\circ$ polar $\times \sim 20^\circ$ azimuthal field of view.

3 The observational data

Pitch angle distributions are shown as functions of time for two specific days: 26 October 1999 and 12 September 2000. These days were chosen to demonstrate certain characteristics that are commonly observed by the IES and IPS on Polar. The features in the data that will be discussed on these two days are generally not unique, but were chosen for their clarity.

Polar was launched in 1996 with an apogee over the northern pole, which then precessed southward, pushing the equatorial crossings further away from the earth. For the following two events, the apogee of the orbit was near local midnight. As the satellite passed through the equatorial region, it was moving along an outbound path, from the southern to the northern hemisphere.

3.1 26 October 1999

Electron butterfly PADs are observed by the IES across all available energy channels as Polar crosses the nightside magnetic equatorial equator as displayed in Fig. 1. Additionally, the relative strength, as well as the timing of the onset of the butterfly PADs are approximately constant throughout the energy range of the IES.

Figure 2 displays the pitch angle distributions of energetic ions as observed by Polar as a function of time from 11:30 UT until 14:30 UT. In all, sixteen energy channels are displayed with the title of each indicating the central energy of the channel. There is contamination from the sun that is observed in the lowest two energy channels occurring with pitch angles under $20^\circ$.

For ions with energies between 48.1 keV and 459 keV, the pitch angle plots from IPS indicate a pronounced butterfly PAD when Polar is near the nightside magnetic equatorial plane from 12:30 UT.
until 13:30 UT. The specific onset and duration of the butterfly PAD is dependent upon the observed energy channel. In general, the butterfly shape is observed in the PAD first in the more energetic channels. In orbital space, this earlier onset corresponds to a slightly lower L-shell, as the spacecraft is outbound during this period. As the energies of the ions increase, the strength of the butterfly PAD decreases. For the highest three energy channels, the incident fluxes are low enough such that butterfly PADs cannot be accurately determined.

Pancake PADs are also observed in addition to the butterfly PADs at the same time, but the pancake PADs occur only at lower energy levels. The lowest four energy channels have a PAD that is peaked at $90^\circ$, while the 48.1 keV channel shows both butterfly and pancake PAD components. This creates two distinct populations that co-exist in the the nightside magnetic equatorial region. Here, less energetic ions are dominated by $90^\circ$ pitch angle ions, and in the more energetic regime, the opposite occurs where more field aligned ions have the dominant fluxes.

3.2 12 September 2000

Like the electrons observed in the 26 October event, Fig. 3 shows that IES detects butterfly PADs across the instrument’s entire energy range, with the $90^\circ$ dropout occurring at almost identical times and relative intensities. This is a behavior that is not observed with the IPS detection of the protons.

Figure 4 displays the pitch angles of energetic ions as observed by Polar as a function of time from 5:00 UT until 7:00 UT. In all, sixteen energy channels are displayed with the title of each indicating the central energy of the channel. Like the 26 October event, IPS measures simultaneous high energy butterfly and low energy pancake PADs.

Also similarly, there is a $90^\circ$ pitch angle peak that is nested within a butterfly PAD in the 35.4 keV channel. The plots also show that when injections occur in the lowest energy channels, temporally, they begin at $90^\circ$ and expand to more field aligned pitch angles. Spatially, this indicates in the injection, the $90^\circ$ pitch angle particles are observed further inward than particles of other pitch angles.

4 Single particle motion modeled in a simulated magnetosphere

Using the Tsyganenko simulated magnetosphere (Tsyganenko, 1995; Tsyganenko and Sitnov, 2005), the differential equation of motion of a particle with mass $m$, and charge $q$ is,

$$\frac{d}{dt} \left( \frac{m}{d} \frac{dr}{dt} \right) = q \left( \frac{dr}{dt} \times B + E \right).$$

(1)

The position of the particle has a solution as a function of time beginning with an initial position and velocity. These solutions can be numerically estimated to yield a path of motion for electrons and ions with a given initial pitch angle and energy.

Once the magnetic field topology is estimated using the T96 model, a Runge-Kutta type method is used to estimate these differential equations that govern the motion of the particles to yield the next
point in space in the time sequence. The particle simulations used the “Trajgen” code developed by Sullivan (2002). These increments can then be compiled over a time progression to show the suggested path a particle may take.

Energetic ions were simulated to progress along their bounce and drift paths backward in time to determine the origins of the particles observed by the IPS sensor. Ions were simulated at $30^\circ$, $60^\circ$, and $90^\circ$ pitch angles with energies of 26.2 keV and 327 keV for the two aforementioned days. The higher energy simulations were run to simulate 30 minutes of drifting, which was approximately a single drift orbit. The lower energy simulations were also simulated to complete about a single drift orbit, which was approximately 5 hours.

Figures 5 and 6 represent traces of ions that originate at Polar’s location at 13:27 UT, which in GSM coordinates is: $x = -6.17R_E$, $y = 1.85R_E$, and $z = -0.34R_E$. The simulations indicate that when Polar observes a butterfly PAD at higher energies, the drift paths seem to be closed at all pitch angles. The $90^\circ$ pitch angle ion elevates to a high latitude Shabansky orbit (Antonova and Shabansky, 1975; Mead, 1964; Shabansky, 1971) as it drifts around to the dayside region. Where a pancake PAD is observed at lower energies, the simulations yield closed drift paths for $30^\circ$ pitch angle particles. However, the low energy $60^\circ$ and $90^\circ$ pitch angle ions observed by Polar seem to originate from the dawn flank of the magnetopause.

5 A source population

The ion pitch angles presented in Figures 2 and 4 both show ion injections that occur in the lower energy ranges. When the IPS detects an injection, the ions with a pitch angle of $90^\circ$ are measured first, with more field aligned particles detected afterward. This process can be seen in the 26.2 keV channel on the 26 October event beginning approximately at 12:18 UT and on the 19.9 keV channel on the 12 September event beginning approximately at 5:12 UT.

With the particle tracer, a hypothetical 26.3 keV ion source is created in the dayside magnetosphere, and particles of various pitch angles are modeled forward in time such that the $90^\circ$ ions drift westward to the location that Polar observes the beginning of an injection at 5:12 UT. The resulting particle paths shown in Fig. 7 indicate that the $90^\circ$ pitch angle particles have magnetic equatorial crossings with the shortest radial distance to the earth upon drifting to the nightside. In this simulation, the $30^\circ$ pitch angle ion migrated the furthest away from the earth as it drifted into the nightside region where Polar observes the ion injections.

In both of these observations, the Polar spacecraft is moving along an outbound trajectory in the nightside equatorial region. The earlier observations of the of the $90^\circ$ pitch angled ions corresponds to a lower L-shell value than when the more field aligned particles are observed. This pattern is indicative of an isotropic source on the dayside, similar to the pattern shown in Fig. 7.
6 Ion energy spectra

During the butterfly PAD observed by Polar on 12 September 2000, there is an additional population with a peak intensity at a 90° pitch angle. Using the sixteen available energy channels on the IPS, it is possible to create energy spectra from the ion measurements. Figure 8 shows the observed ion spectra for populations with 30° and 90° pitch angles. The particles intensities were averaged over a half hour time interval from 5:48 UT until 6:18 UT.

The ions with 30° and 90° pitch angles are shown to be distinct populations with their own spectra, with the 90° pitch angle particles dominating at low energies, but falling off more quickly than the 30° pitch angle ions. It may then be concluded that the injection of locally mirroring particles that are observed by Polar under 60 keV are a population distinct from the butterfly distribution commonly observed in the nightside equatorial region.

7 Conclusions

Butterfly PADs are exemplified in the electrons at all energies measured by the IES. Similarly, the onset time and duration of the butterfly PAD are not dependent on the energy.

The ions, however, demonstrate an energy dependent bifurcation in the observed PADs. Above energies of \( \sim 60\text{keV} \), butterfly PADs exist in the ion population that is similar to those observed in the electrons. A higher energy level corresponds to an earlier detection of the onset of the butterfly PAD. For ions with energies below \( \sim 60\text{keV} \), there appears to be a source centered upon a pitch angle of 90°. These source particles are on the same gradient drift paths as the electrons and higher energy ions, which have been modeled backward in time to show they contacted the magnetopause.

The magnetopause can act simultaneously as a sink for high energy ions and electrons with pitch angles near 90° via magnetopause shadowing, and as a source for ions with pitch angles near 90° below \( \sim 60\text{keV} \). This source population seems to be composed of a series of injections where the 90° pitch angle ions are observed first followed progressively later by off equatorially mirroring particles.

The modeling efforts have produced results that are consistent with the interpretation that the magnetopause may be able to simultaneously act as both a source and a sink for equatorially mirroring charged particles.

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References


**Figure Captions**

**Fig. 1.** Electron pitch angle intensities plotted as a function of time for ten different energy levels from 20 keV to 400 keV. Observations are from 10:30 UT until 14:00 UT on 26 October 1999.

**Fig. 2.** Ion pitch angle intensities plotted as a function of time for sixteen different energy levels. Observations are from 11:30 UT until 14:30 UT on 26 October 1999.

**Fig. 3.** Electron pitch angle intensities plotted as a function of time for ten different energy levels from 20 keV to 400 keV. Observations are from 3:30 UT until 7:00 UT on 26 October 1999.

**Fig. 4.** Ion pitch angle intensities plotted as a function of time for sixteen different energy levels. Observations are from 5:00 UT until 7:00 UT on 12 September 2000.

**Fig. 5.** 26.2 keV Ions simulated backward in time beginning at 13:27 UT on 26 October 1999 for initial pitch angles of 30°, 60°, and 90°.

**Fig. 6.** 327 keV Ions simulated backward in time beginning at 13:27 UT on 26 October 1999 for initial pitch angles of 30°, 60°, and 90°.

**Fig. 7.** 26.2 keV Ions simulated forward in time beginning at 3:47 UT on 12 September 2000 with initial pitch angles of 30°, 60°, and 90°, with display a radial gradient to their respective drift paths.

**Fig. 8.** Logarithmic plot of the mean flux of ions from 5:48 UT until 6:18 UT as a function of the ion energy. This half hour time period encompasses the butterfly PAD observed by Polar on 12 September 2000. 30° and 90° pitch angles are shown to have unique energy spectra.
Fig. 1. Electron pitch angle intensities plotted as a function of time for ten different energy levels from 20 keV to 400 keV. Observations are from 10:30 UT until 14:00 UT on 26 October 1999.
Fig. 2. Ion pitch angle intensities plotted as a function of time for sixteen different energy levels. Observations are from 11:30 UT until 14:30 UT on 26 October 1999.
Fig. 3. Electron pitch angle intensities plotted as a function of time for ten different energy levels from 20 keV to 400 keV. Observations are from 3:30 UT until 7:00 UT on 26 October 1999.
Fig. 4. Ion pitch angle intensities plotted as a function of time for sixteen different energy levels. Observations are from 5:00 UT until 7:00 UT on 12 September 2000.
Fig. 5. 26.2 keV Ions simulated backward in time beginning at 13:27 UT on 26 October 1999 for initial pitch angles of 30°, 60°, and 90°.
Fig. 6. 327 keV Ions simulated backward in time beginning at 13:27 UT on 26 October 1999 for initial pitch angles of 30°, 60°, and 90°.
Fig. 7. 26.2 keV Ions simulated forward in time beginning at 3:47 UT on 12 September 2000 with initial pitch angles of 30°, 60°, and 90°, with display a radial gradient to their respective drift paths.
Fig. 8. Logarithmic plot of the mean flux of ions from 5:48 UT until 6:18 UT as a function of the ion energy. This half hour time period encompasses the butterfly PAD observed by Polar on 12 September 2000. 30° and 90° pitch angles are shown to have unique energy spectra.