

IMAGING THE PLASMA SHEET WITH ENERGETIC IONS FROM THE POLAR SATELLITE

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Abstract. Between 10 and 11 UT On September 3, 1997, the POLAR satellite crossed the equatorial magnetosphere at 1500 local time. Three components of the H^+ and O^+ ion distribution observed at $L=4$ had broad maxima in the number flux at 12, 50 and 120 keV/e. Such multiple peaked ion distributions are frequently observed in the dusk side magnetosphere. We use a simple model to show that the observed ion distributions are consistent with origins in the plasma sheet. Our model predicts that the ions were created with significantly lower energies in localized regions at times associated with the two intervals of magnetic activity that occurred prior to the POLAR observations. This result suggests that, under special conditions, we may be able to determine remotely some characteristics of the plasma sheet from observations made in the inner magnetosphere.

1. Introduction

The energetic ion population found at geocentric distances from 6.6 (geosynchronous orbit) to $4 R_E$ (i.e. on McIlwain L shells from 6.6 to 4) near the equator has been extensively studied [e.g. McIlwain, 1972, Smith and Hoffman, 1974, Lennartsson et al., 1979, Ejiri et al, 1980, Strangeway and Johnson, 1984, Kistler et al., 1989]. Energetic ions in this region are on what are called open drift paths. These paths take ions from the plasma sheet, through the dusk side and eventually out of the magnetosphere. Ions on open drift paths do not directly become part of the permanent ring current. Properties of these ion distributions in conjunction with sophisticated modeling have been used to investigate the Earth's convection electric field [e.g. Toivanen, 1997]. Most of the observations of ions on L shells inside of geosynchronous orbit have been made from satellites in equatorial orbits. Observations from polar orbiting satellites [e.g. Strangeway and Johnson, 1984, Shirai et al. 1997 and Kistler et al. 1998] have been made at lower altitudes significantly removed from the equator where charge exchange and off equatorial effects complicate the use of ion spectra to infer large scale magnetospheric configuration or dynamics.

NASA's POLAR satellite was launched into a 86 deg inclination orbit in February 1996 and includes a full complement of state-of-the-art particle and fields instruments. More important for the present study is the fact that the POLAR orbit samples the near equatorial region at geocentric distances from 3 to $5 R_E$, significantly higher than previous polar orbiting satellites. Sensitive instruments on POLAR allow determination of complete mass resolved ion spectra over the range from 15 eV to 200 keV/e as a function L at a nearly constant local time.

2. Observations

[Figure 1](#) presents spectrograms of H^+ and O^+ ion plasma obtained from the Toroidal Imaging Mass-Angle Spectrograph (TIMAS, Shelley et al. [1995]) and the MICS sensor of the Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE, Chen et al., [1997]). These ion mass spectrometers provide overlapping energy coverage from 0.015 to 200 keV/e. Data are displayed in energy (ordinate) vs. L (abscissa) format with the number flux in units of ions/cm²-s-sr-keV/e encoded by the color bars. [Figure 1](#) displays data acquired from 0930 to 1130 UT on September 3, 1997 at pitch angles of $90 \pm 30^\circ$. Data from TIMAS are in the top two panels and CAMMICE /MICS in the bottom two. Detailed analysis shows the ion spectra to be weakly peaked at 90° throughout this interval in agreement with previous observations. The H^+ and O^+ ion distributions between $L=4.5$ and 5.0 below 10 keV in the top two panels are not real. These artifacts are associated with the subtraction of a background counting rate significantly higher than the signal counting rate.

The most striking features in [Figure 1](#) are the multiple maxima in the number flux at specific energies that decrease with increasing L. The lower two energy bands (alternatively, the lack of ions in the 20 keV range near $L=4$) are often observed on dusk side crossings of the magnetosphere. The lower energy bands are particularly well developed in this case. In the first 10 days of September 1997, similar features were detected in over half of the dusk crossings. The >100 keV flux maximum at $L=4$ is less frequently observed. We note also that the 100 keV feature extends to lower L and has a slightly different energy vs. L dependence than the lower two energy bands.

Our analysis focuses on the interval in [Figure 1](#) when POLAR was between L of 4 and 6 moving southward and downward from $L=6$ at 10:20 UT (geomagnetic latitude 28° , $r/R_E=5.7$) to $L=4$ at 10:57 (geomagnetic latitude 14° , $r/R_E=4.8$). The peak energies in the H^+ and O^+ distributions occurred at the same energies. They were observed at 12, 50, and 120 keV at $L=4$ and 7, 25, and 35 keV at $L=6$.

The observations were made during a period of extremes in geomagnetic activity. [Figure 2](#) presents the AE/AO section of the on-line magnetic activity plot provided by the WDC-C2, Kyoto, for the period from 0000 to 1200 UT on September 3, 1997. (The AO index is the sum of the AL and AU indices; AE is the difference.) Eight stations were included in this preliminary index except for a brief interval near 05 UT. [Figure 2](#) shows a period of low to moderate activity from 0400 to ~ 0630 , a quiet period from ~ 0630 to ~ 0830 , a period of strong activity (AE peaking at a value greater than 500) until ~ 1000 , and relatively quiet conditions from 1000 to 1200 UT during the interval the data in [Figure 1](#) were acquired. On-line data from the LANL energetic particle instruments are consistent with the indices in

3. Model

In this section we make some simplifying assumptions about the energization and transport of ions from the distant plasma sheet. Our assumptions are motivated by recent results from the Geotail satellite [Nagai et al., 1998, Fairfield et al. 1998]. These papers report localized energization regions in the plasma sheet associated with substorms. Additionally, the observation of Angelopoulos et al. [1993] show that, at all levels of magnetic activity, the plasma sheet is characterized, on average, by slow (~ 50 km/s) Earthward drift, except for the $<10\%$ of the time that bursty bulk flows are observed. Our analysis focuses on the trapped ion population. We do not consider electrons or the field aligned component of the ion distribution.

Our model is a simple hybrid model that traces particles backward in time from POLAR observations. Specifically inside $X=-10 R_E$, we use a T89 magnetic field model [Tsyganenko, 1989] and a constant cross tail electric field 0.45 mV/m to estimate the time required for ions to drift backward in time from $L=4$ and 6 at 1500 local time to $X=-10 R_E$ [Toivanen, 1997]. The gradient-B drift term is dominant in this region. Tailward of $X=-10 R_E$, we assume that ions drift Earthward with an average velocity in the range $30-50$ km/s. We also assume a static magnetic field in the tail characterized by the values $50, 20,$ and 10 nT at $X = -10, -30,$ and $-60 R_E$, respectively. The location of the source populations is postulated to be in the plasma sheet ($X < -10 R_E$) and associated with substorms. Using the indices in Figure 2, we infer that substorms did not occur between about 0645 and 0830 or after 1000 UT. The Table below summarizes the results of our model.

	L=4			L=6		
Component (keV)	12	50	120	7	25	35
UT at position						
POLAR	1100	1100	1100	1030	1020	1020
$X=-10R_E$	0740	<u>0930</u>	1000	0700	<u>0850</u>	<u>0920</u>
$X=-30R_E$	<u>0645</u>	0830	<u>0900</u>	<u>0600</u>	0750	0830
$X=-60R_E$	0515	0705	0735	0505	0655	0800
Energy at the inferred Source (KeV)						
	0.6	6	6	1	10	14

This Table presents, for each peak in the energy distribution, observed at $L=4$ and 6 , the peak energy, the time of observation at POLAR, and the inferred time ions would have been at three positions in the plasma sheet. The time and location of the inferred source populations (indicated by underlining in the Table) are chosen to be the nearest to the Earth during a substorm. As noted above, we assume that substorms did not occur between about 0645 and 0830 or after 1000 UT. The model shows that the source populations are isolated in space and time.

The energy of the inferred source populations are given in the last row of the Table. The inferred source energies are determined from the ratio of magnetic field intensity in the plasma sheet and at the equator on field lines at $L=4$ and 6 (i.e., conservation of the first adiabatic invariant). These energies are in the range of those found in the plasma sheet [e.g. Peterson et al. 1981]. We note that the 120 (35) keV component at $L=4$ (6) appears to come from both near and mid regions of the plasma sheet. The lowest energy component appears to have originated before 0700 UT in the mid ($X \sim -30 R_E$) and the middle energy component from the near ($X \sim -10 R_E$) regions of the plasma sheet.

4. Discussion

If the assumptions noted in Section 3 are valid and if the uncertainties in ion travel times in the simple model we have used are small compared to the spatial and temporal extent of energized ion distributions in the plasma sheet, then we have shown that, at least on September 3, 1997, it is possible to obtain some information about the spatial and temporal distribution of energetic plasma in the plasma sheet from observations made in the inner magnetosphere. Here we examine the reliability of the assumptions we have made in our analysis.

The basic assumption we have made is that the characteristic energy of the plasma sheet ion population is not uniform in space or time. In particular we assume there are relatively isolated patches created in association with substorms where the ions have energies that are significantly differentiated from a quiet background population. Our analysis relies on the time dispersion associated with gradient drift of the ions from $X=-10$ to 1500 MLT in the inner magnetosphere. The $0.5-1$ keV ion population typical of the quiet plasma sheet requires many more hours to travel to the dusk side POLAR location than more energetic components. Figure 3 illustrates our model in cartoon format. The creation of regions of energized plasma in the near and mid tail at different times and the subsequent transport of those populations to the POLAR orbit are indicated schematically. Recent results from the Geotail satellite [e.g. Nagai et al., 1998, and Fairfield et al. 1998] suggest that this is a good assumption and provide information about the temporal and spatial scale sizes of the patches of energized ions. The model we have used, however, is not sufficiently developed to take advantage of the statistical information about these scale sizes.

The assumption of a constant Earthward drift of ions in the plasma sheet is reasonably good for the type of analysis we are performing.

Angelopoulos et al. [1993] have shown in quite some detail that the instantaneous flow pattern can not be so simply characterized, but that for the hour time scales relevant for our analysis, it must be. We have used a drift value of 40 km/s earthward, independent of position in the plasma sheet. Angelopoulos et al. and Nagai et al. [1998] provide information about the average flow velocity as a function of X and Y in the plasma sheet which we have not used here.

Earthward of $X=-10 R_E$ the model applies gradient-B drift to the ions, but the ExB drift is still significant and depends on the electric field model. Recent results [e.g. Rowland and Wygant, 1998] suggest that the electric field model we used and more sophisticated models used by others may significantly underestimate the temporal and spatial variability of the field in the inner magnetosphere.

We compared the drift times from POLAR to $X=-10 R_E$ using the two electric field models used by Toivanen [1997] and found differences between the results on the order of a few minutes for the lowest energy ions. The present results shown in Table above are therefore uncertain to at least 10, and perhaps more, minutes.

Li et al [1998] have shown that time dependent electric fields in the inner magnetosphere can account for many of the features in energetic electrons found at synchronous orbit ($L=6.6$). The data and analysis presented here can not rule out the possibility that time dependent electric fields are responsible for one or more of the features in Figure 1. We note, however, that the two lower energy components extend to $L=10$, whereas the 120 keV (at $L=4$) component does not. This suggests that the source region for the lower energy components lies outside of $L=10$ where the effects of time dependent electric fields are significantly reduced.

5. Conclusion

We have shown an example of how information about (i.e., images of) temporal and spatial features in the plasma sheet might be obtained from energetic particle populations measured by the POLAR satellite, in the afternoon sector inner magnetosphere. Our analysis assumes that there are temporally and spatially restricted regions of ion energization in the plasma sheet. We proceed to show that the data obtained on September 3, 1997 are consistent with our assumptions. The present analysis does not prove either that restricted temporal/spatial features in the plasma sheet are associated with substorms or that our approach can be extended to provide a method to obtain detailed information about the plasma sheet from near Earth observations. The analysis presented here, however, suggests that our approach should be investigated in more detail, perhaps using *in-situ* plasma sheet observations and more sophisticated models.

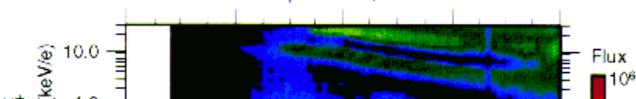
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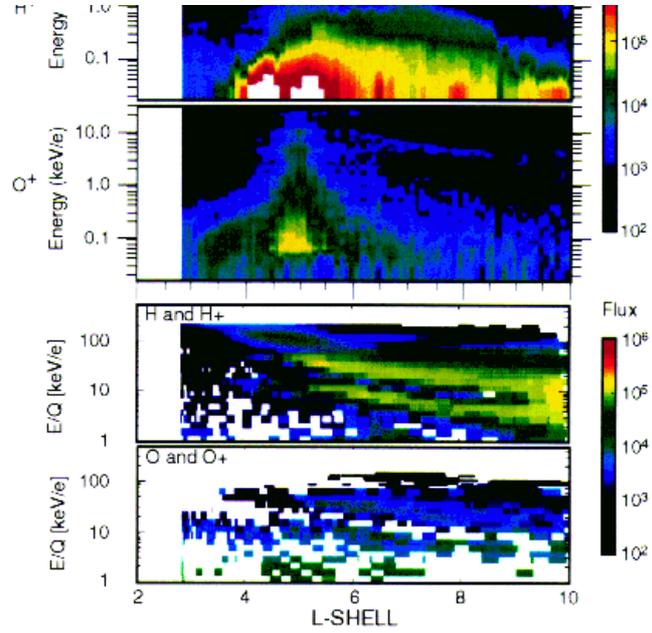


Figure 1. Observed ion energy spectra. ([Larger Version of Figure 1](#))

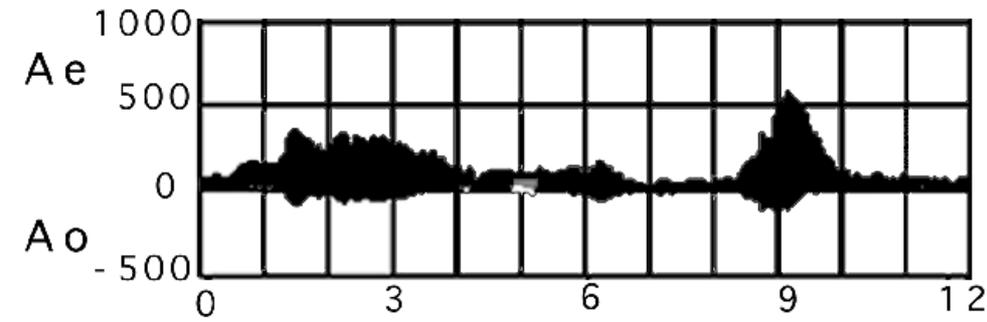


Figure 2. Preliminary AE/AO indices.

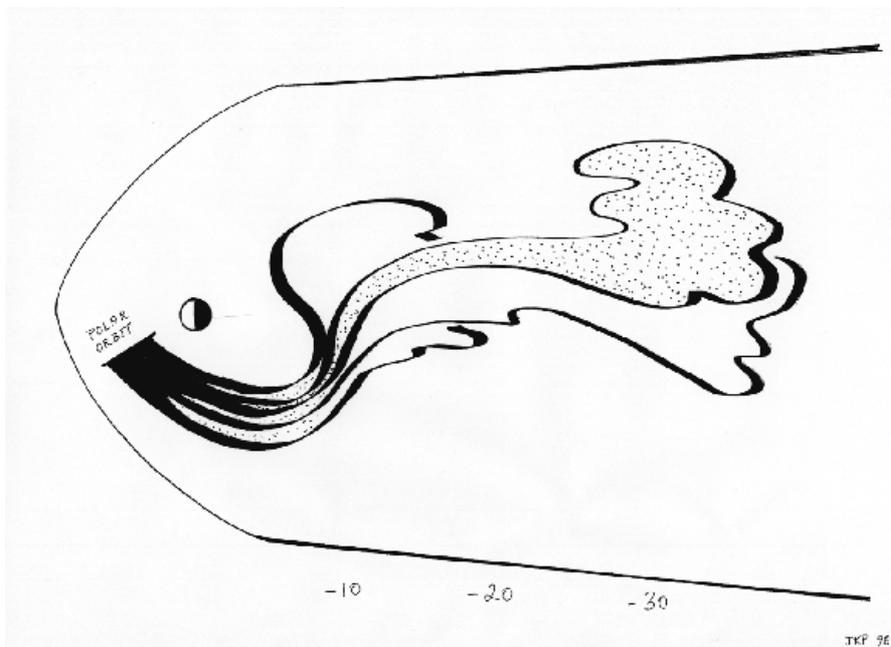


Figure 3. Our model in cartoon format.