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Factors controlling the diamagnetic pressure in the polar cusp

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Abstract. The solar wind has direct access to the polar cusps although the plasma may be processed first by reconnection. The energy density of the polar cusp plasma is expected to be controlled by the component of the unshocked solar wind dynamic pressure along the normal to the cusp/magnetosheath interface. The factors controlling this angle are the local time of the observation and the dipole tilt angle. We use Polar observations of the magnetic field and plasma to identify the polar cusp, and the change in magnetic pressure in the cusp to calculate the peak diamagnetic pressure of the plasma. As expected this pressure is directly proportional to the solar wind dynamic pressure in quantitative agreement with expectations. When the dipole tilts more toward the Sun, the angle between the solar wind flow and the magnetopause normal is smaller, and the pressure is higher, and when it tilts away from the Sun, the pressure is less. For large tilts away from the Sun, for local times far away from noon and for low solar wind dynamic pressure the diamagnetic depression marking the polar cusp is too weak to be resolved by the magnetometer.

Introduction

The polar cusps are present in the earliest and simplest model of the magnetosphere, that of *Chapman and Ferraro* [1930]. In this model the solar wind plasma has direct access to the magnetosphere all the way down to the ionosphere. In our modern picture of the magnetosphere the shape is, of course, more bullet like but two cusps, at high northern and southern latitudes, are still present. An important difference in the modern picture is the presence of reconnection: subsolar reconnection for southward IMF and high latitude reconnection for northward IMF. It is possible that acceleration accompanying reconnection and the magnetic pressure in the cusp plasma alters the properties of this plasma, and in particular its energy density.

The location of the polar cusp has been studied by spacecraft at both low and high altitudes. At low altitude the cusp is detected through its plasma signature that remains largely unaltered along the cusp whereas the magnetic field depression due to the cusp plasma, a characteristic signature of the cusp at high altitudes, is insignificant at low altitudes. *Russell et al.* [1971] first reported a substantial reduction of magnetic field at the high altitude (~5 Re) polar cusp region seen by the OGO 5 spacecraft, due to the diamagnetic currents generated by the particles from magnetosheath. They compared the diamagnetic energy density implied by the field depression with the measured electron energy density, and predicted the proton energy density in the cusp.

Most recently *Eastman et al.* [2000] and *Boardsen et al.* [2000] have completed a comprehensive study of the plasmas and the magnetopause in the neighborhood of the cusp. They find, perhaps paradoxically, that the solar magnetic (SM) coordinates order the plasma properties best but solar magnetospheric (GSM) coordinates order the boundary positions better. Both papers stress the importance of the tilt angle in determining the properties of the near cusp magnetosphere, a conclusion fully consistent with the results we report herein.

Previously we have examined how the location of the polar cusp in latitude and local time responds to solar wind conditions [*Zhou et al.*, 2000]. In this paper, Polar observations are used to investigate the energy density in the cusp plasma from 5-9 Re. We identify and characterize the polar cusp with Polar magnetic field data [*Russell et al.*, 1995], using Hydra [*Scudder et al.*, 1995] and Timas [*Shelly et al.*, 1995] key parameter data to confirm our identification. We then determine the dependence of the cusp pressure on the solar wind dynamic pressure, magnetic local time and dipole tilt angle.

Data Analysis

The Polar spacecraft is in a highly elliptic polar orbit with apogee at 9 Earth radii (R_E) over the north pole. During part of the year the orbit lies close to the X-Z plane in solar magnetic coordinates and the satellite cuts through the region of the polar cusp nearly orthogonal to the planes of constant invariant latitude. Polar detects cusp plasma over a wide range of MLT, ~6 hours, even further for high solar wind dynamic pressure [*Zhou et al.*, 2000]. We can identify the cusp by its magnetosheath-like (high density and low temperature) plasma. At high altitudes, the plasma energy density is a significant fraction of the ambient magnetic pressure and causes a diamagnetic depression and fluctuations in the magnetic field strength. In this study we use the coincident plasma and magnetic signatures to identify the cusp and the magnetic signature to provide the quantitative measurement of the energy density of the plasma. For details of the criteria for identifying the cusp and examples of cusp crossings, please see *Zhou et al.* [2000].

To measure the magnitude of the magnetic depression due to the stagnant magnetosheath-like plasma in the polar cusp region, we examine the diamagnetic pressure, the difference in

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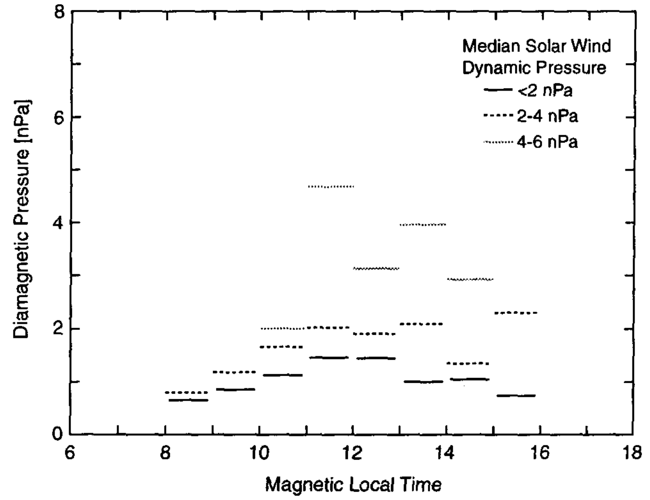

Figure 1. The magnetic local time distribution of the peak diamagnetic pressure for different solar wind dynamic pressure ranges. The solid black, dashed, and gray bars correspond to the medians for dynamic pressures of <2, 2-4, and 4-6 nPa respectively.

magnetic energy density between the observed magnetic pressure and the magnetic energy density in the absence of plasma, i.e.

$$\text{diamagnetic pressure} = (B_0^2 - B_{MFE}^2)/2\mu_0 \qquad (1)$$

To remove the changes in field strength due to the motion of the spacecraft through spatial gradients we use the Tsyganenko 1996 model [*Tsyganenko*, 1996] to subtract from the observations as the first step in identifying the cusp. Once the center of the cusp is identified by the minimum in the magnetic field, the total field pressure at the cusp center in the absence of plasma, $B_0^2/2\mu_0$, is calculated extrapolating the field across the cusp and compared with the observed minimum energy density in the magnetic field, $B_{MFE}^2/2\mu_0$. The difference is the perpendicular energy density of the cusp plasma. We are not sensitive in this analysis to the parallel energy of the plasma.

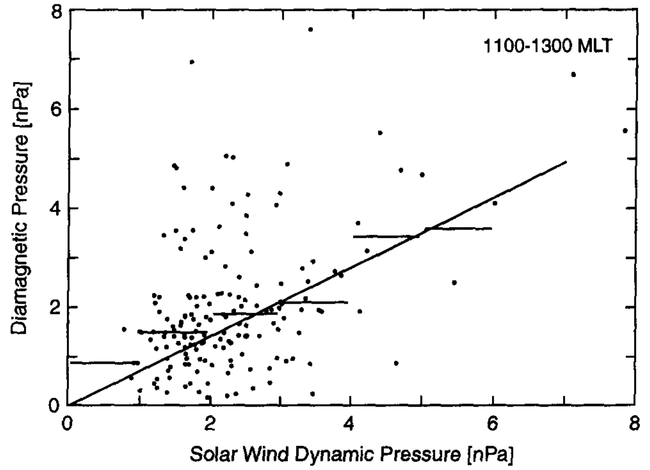

Figure 2. The variation of diamagnetic pressure with solar wind dynamic pressure. The dots are observations near noon (1100-1300 MLT). The short bars are medians. The straight line is the prediction from the magnetopause shape from Hawkeye observations [Zhou et al., 1997].

We have tested that the observed increase in the plasma thermal energy is equal to the magnetic field drop. An example of one of these tests is the cusp crossing shown in the top left panel of Figure 1 of *Zhou et al.*, [2000]. Here the diamagnetic pressure calculated by the above definition is 0.81 nPa. The plasma density as measured by Hydra is 38 cm^{-3}, the electron temperature, T_e, is about 40 eV and the ion temperature, T_i, from Timas is about 100 eV. So the thermal energy from the electrons and ions is: $nk(T_e+T_i) = 0.84$ nPa and is consistent with our assumption. Since the magnetometer is a very precisely calibrated instrument with an absolute calibration on Polar to better than 0.01% we use the magnetic readings for the absolute measurements of the energy density. We do not use the magnetic measurements once the magnetic signature is less than 1 nT.

Solar Wind Control of the Diamagnetic Pressure

Figure 1 shows the magnetic local time distribution of the peak diamagnetic pressure. It reaches a maximum at about 12 MLT. We divided the data set into bins of different solar wind dynamic pressure because we expect that the solar wind dynamic pressure should modulate the diamagnetic pressure. The short bars show the medians. For a fixed solar wind range (e.g., for $\rho v^2 < 2$ nPa and $2 < \rho v^2 < 4$ nPa), the depression of the magnetic field is greater near local noon and decreases away from noon. Also, the diamagnetic pressure is greater for greater solar wind dynamic pressure. To see this latter trend more clearly, we fix the magnetic local time. Figure 2 shows that the diamagnetic pressure varies with the solar wind dynamic pressure near local noon. The black dots are observations in the time sector of 1100-1300 MLT. The short bars are the medians.

As stated before, the diamagnetic pressure is provided by stagnant plasma trapped in the cusp region. These particles originate from the solar wind either by diffusion or reconnection. The expected zeroth order relationship between this diamagnetic pressure and the unshocked solar wind dynamic pressure is:

$$\text{diamagnetic pressure} = \rho v^2 \cos^2 \alpha \qquad (2)$$

where ρv^2 is the solar wind dynamic pressure, α is the angle between the magnetopause normal direction and the solar wind direction [*Petrinec and Russell*, 1997].

The angle α can be estimated from a magnetopause model. Since these observations are at high altitudes, we use the magnetopause shape at high altitudes observed by Hawkeye [*Zhou and Russell*, 1997]. Near the cusp, $\alpha = 33°$ in the noon-midnight meridian. So, $\cos^2 \alpha = 0.70$ at noon. This slope is plotted as a straight black line in Figure 2. This straight line fits the medians well.

For all time sectors, data were plotted in Figure 3. The solid black, dashed, light dashed and gray lines correspond to

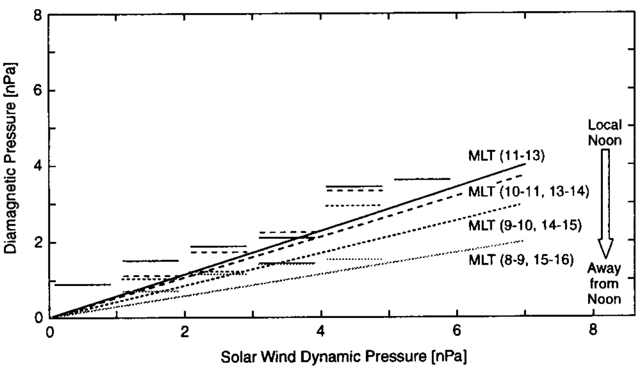

Figure 3. The variation of diamagnetic pressure with solar wind dynamic pressure at different local time sectors. The solid black, dashed, light dashed and gray bars correspond to the medians observed in the time sectors of (11-13), (10-11, 13-14), (9-10, 14-15), and (8-9, 15-16) MLT respectively. The different lines are from magnetopause model of Petrinec and Russell [1993, 1995] for different local times.

noon (11-13) MLT, (10-11, 13-14) MLT, (9-10,14-15) MLT, and (8-9, 15-16) MLT respectively. For a fixed MLT range, the diamagnetic pressure increases with solar wind dynamic pressure. The diamagnetic pressure has the greatest value near magnetic local noon from 11-13 MLT.

We do not have an empirical model for the high latitude magnetopause as a function of local time. If we use the low-latitude magnetopause model of Petrinec and Russell [*Petrinec and Russell*, 1993, 1995], we find $\alpha = 41°$ near the cusp in the noon-midnight meridian. So, $\cos^2 \alpha = 0.57$ at noon. Equation (2) is plotted as straight lines in Figure 3 for different local times. The black line is the relationship at noon. The other line styles (dashed, light-dashed, and gray lines) correspond to this equation at 1100 or 1300, 1000 or 1400, and 0900 or 1500 MLT respectively. Clearly the low latitude model does not apply to the high latitude magnetopause. For instance the 1100-1300 LT predicted dependence that was in close agreement with observations for the high latitude shape model in Figure 2 underestimates the pressure in Figure 3 using the low latitude shape as do all the other lines. Nevertheless we do obtain qualitative agreement. Away from local noon, the diamagnetic pressure decreases in model and data, but the predicted slope is smaller than observed.

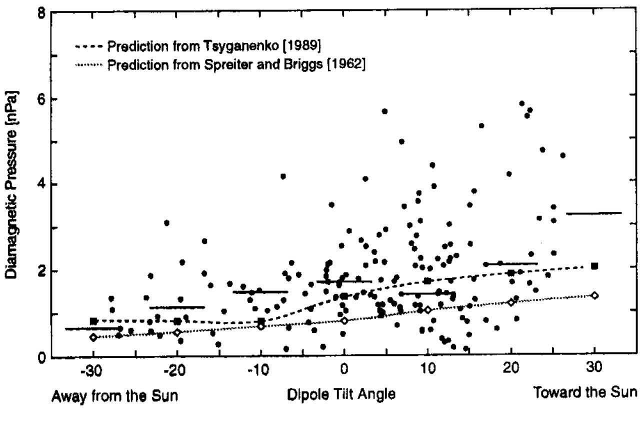

Figure 4. The tilt angle versus the diamagnetic pressure near noon (11-13) MLT. The bars are the medians. The dashed and gray-dashed lines are predictions from the Tsyganenko 1989 vacuum model and the Spreiter and Briggs [1962] aerodynamic model.

In addition to this local time dependence, the diamagnetic pressure also shows strong dependence on the dipole tilt angle. Figure 4 shows the tilt angle versus the diamagnetic pressure for all observations near noon (1100-1300 MLT). Here all diamagnetic pressures have been normalized to a solar wind dynamic pressure of 2.33 nPa using the linear relationship shown in Figure 2. When dipole tilts away from the Sun, the diamagnetic pressure is smaller. This is not surprising - because when the dipole is tilted toward the Sun the normal to the magnetopause makes a smaller angle to the flow direction of the undisturbed solar wind and the $\cos^2 \alpha$ factor, described above, is larger. In this figure, the bars show the median values.

Figure 4 also includes the predictions from the *Spreiter and Briggs* [1962] aerodynamic model with a gray-dashed line and those from the Tsyganenko 1989 vacuum model [*Tsyganenko*, 1989] with a dashed line. The diamagnetic pressure is calculated with (1) and all crossings of the cusp from 11 to 13 MLT are used independent of solar wind pressure. The angle α is measured from models for different tilt angles. The average solar wind dynamic pressure for our near noon cusp encounters of 2.33 nPa is used in this calculation. For large tilts away from the Sun, and especially for low solar wind dynamic pressure, the polar cusp falls below the 1 nT threshold we have set for the measurement. Nevertheless the figure shows that the median values are qualitatively consistent with the models. Quantitative agreement would require altering the shape of these inviscid models especially near the cusp.

Summary

From the 459 polar cusp crossings that we identified in the Polar observations during the period, March 1996 to December 1997, we conclude that the diamagnetic pressure in the cusp varies with local time, tilt angle and solar wind dynamic pressure as expected if the plasma had free entry into the magnetosphere. The variation with solar wind dynamic pressure can be quantitatively predicted from the geometry of the magnetosphere using a realistic magnetopause shape. The local time variation of the cusp pressure is qualitatively consistent with the varying angle of incidence of the solar wind with the magnetopause away from noon. We do not have an adequate three-dimensional model of the shape of the near cusp magnetopause to predict the cusp plasma pressure away from noon. However, it may also be that only the central portion of the cusp near noon contains the full expected cusp plasma pressure. The cusp certainly has a gradient in the plasma pressure in the latitudinal direction that Polar traverses each orbit. Finally we can understand the dependence of the diamagnetic pressure on the tilt angle in terms of the varying angle of the magnetopause normal with tilt. In all, the central cusp is much as *Chapman and Ferraro* [1930] had predicted, despite the occurrence of reconnection on magnetic field lines threading the cusp.

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