The location of the high-latitude polar cusp and the shape of the surrounding magnetopause

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Abstract. Hawkeye magnetic field measurements have been used to determine the location of the magnetopause in the vicinity of the polar cusp. We can clearly distinguish field lines above the cusp from those below the cusp and thus can well identify the statistical location of the cusp. As expected, we find that the location of the polar cusp depends strongly on the dipole tilt angle. However, there appears to be no indication of the magnetopause surrounding the cusp in contrast to models of the cusp that are frequently drawn. At the magnetopause on the noon meridian the cusp is at a latitude of nearly 82° for northward interplanetary magnetic field (IMF) and 80° for southward IMF. This is more swept back than in models such as that of T. Nygårdsko et al. but less swept back than in the computer simulation of C. C. Wu. In our study, both geocentric solar magnetospheric (GSM) and solar magnetic (SM) coordinates are used. GSM coordinates orient the high-altitude polar cusp position slightly better than SM coordinates.

Introduction

The location of the magnetopause has been studied for decades [see, e.g., Corrall and Pectn, 1967], but most of these studies have concentrated on the low-latitude magnetopause. Few spacecraft have had the high-apogee, polar orbit necessary for exploring the high-latitude magnetopause. Two exceptions were the early missions HEOS 2 and Hawkeye, with highly elliptical pole orbits. Even through these missions were quite successful, we still know very little about the solar wind interface with the polar cusp in part because the data from these missions were not completely analyzed.

In this paper we will attempt to rectify this situation partially by using Hawkeye data to determine the shape of the magnetopause at high latitudes and to understand some of the basic physics in this region.

We will compare our results with those of S. M. Pettine and coworkers both at low latitudes and in the tail (Pettine et al., 1991; Pettine and Russell, 1993a, b, 1995a, 1996a). These models agree with those of other researchers obtained under normal solar wind conditions [e.g., Rosleif and Siebeek, 1993] but differ under extreme conditions [Pettine and Russell, 1995b]. In these studies, the shape of the low-latitude and midlatitude day-side magnetopause was obtained from ISN 1 and 2 crossings of the boundary (Pettine and Russell, 1993a, 1994a).

The tail magnetopause position was determined from a local pressure balance condition which constrained the shape of the magnetopause [Pettine and Russell, 1938, 1996c]. From this shape, the position of the magnetopause was determined by integrating from the day-side position. Hawkeye provides data in the region not accessible to ISN 1 and 2, i.e., high latitudes on the day-side and in the near tail, to allow us to find the overall configuration of the magnetopause at high latitudes and to study its behavior.

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Data Analysis

Hawkeye is a polar-orbiting spacecraft with an inclination varying from 80.81° to 81.85°, an apogee varying between 20.28 and 20.92 Rs and a perigee of less than 1.7 Rs. We have examined time series of the magnetic field data at 46-s resolution for the period June 4, 1974, to June 1, 1975. As shown in Figures 1a and 1b, we have identified the magnetopause through its signature in the three vector components of the field and in the declination (D) and inclination (I) angles. Here the inclination angle is the angle between the field and the radius vector minus 90°. I = cos−1(Rp/R, R). -90°. I/2 can also be defined as the angle between the local horizontal plane and the B vector. The declination angle is measured in the horizontal plane about the radius vector, Δ = tan−1(Rp/R, R, R). R is the unit vector from the center of the Earth to the point of observation, B is the direction of the magnetic field in the same system, and the components are measured in the dipole meridian system.

The declination is zero when the projection of the field in the horizontal plane is northward and 90° when the horizontal component of the field points eastward in the direction of the Earth's rotation. The new (1995) Tsyganenko [1986, 1995] and also Tsyganenko and Peradov, 1994, A. T. Tsyganenko, personal communication, 1995] empirical model field and its corresponding inclination and declination angles are also shown in Figure 1. When we identify the magnetopause crossings, we also check the Hawkeye plasma data and the IMF B solar wind data to make sure the crossings are chosen correctly. The field values just inside the magnetopause tell us whether the spacecraft is above the cusp or below the cusp. The field lines point northward (D > 90°) below the cusp and southward (D < 90°) above it. Figure 1a shows an example of measurements below the cusp and Figure 1b shows an example of measurements above the cusp. In both cases the declination is close to the angle expected from the Tsyganenko model, while the inclination shows a substantial difference near the boundary.

For the statistic to hold, on the orbits with multiple crossings we pick only one crossing which is the main crossing, or the "median" one. In total we obtained 305 crossings. Since we expect that the solar wind dynamic pressure and the direction of
the interplanetary magnetic field (IMF) will affect the cusp location, we restrict ourselves to only magnetopause crossings for which there is IMF and solar wind measurements on the IMF 8 spacecraft. This reduces the number of crossings under study to 146. Figures 2a and 2b show the location of the magnetopause crossings in GSM coordinates of the subset of the 146 crossings that were located at magnetopause clock angles (tan θ,ψ) from 67.5° to 112.5°, i.e., within 22.5° of the noon meridian, for northward and southward IMF, respectively. Unless we are in the cusp itself, we do not know where it is exactly, but we can determine whether we are above or below the cusp from the orientation of the magnetic field. Thus we can determine where the cusp is statistically. Here solid circles show the magnetopause crossings above the cusp and open circles show crossings below the cusp. Qualitatively, the cusp is located in the boundary between the solid and open circles. All locations have been normalized by the sixth root of the dynamic pressure to a common pressure of 2 nPa. We have tested the inverse square sixth root dependence separately for high and intermediate clock angles and find that within the calculated uncertainties this relationship is observed just as it is at low latitudes (see, e.g., Perrin and Russell, 1999b).

Effect of Dipole Tilt

While Figures 2a and 2b show statistically when the cusp is found, the overlap between observations above and below the cusp indicates that the cusp location is variable. One possible source of this variability is the dependence of the cusp location on dipole tilt angle. From magnetohydrodynamic (MHD) models (e.g., Wu, 1984) and empirical magnetic field models (e.g., Tsyganenko, 1989a) we expect that the dipole tilt angle will affect the polar cusp position. Figure 3a divides the data of Figure 2 into three tilt angle regions (−15° to −10°, −10° to 10°, 10° to 35°), for all observations obtained near the noon meridian (position angle clock angle from 67.5° to 112.5°). Figure 3b is drawn for intermediate clock angles (45° to 77.5° and 112.5° to 135°), i.e., for plates passing through the subsolar point but more than 45° from the GSM equator and more than 22.5° from the noon meridian. For both clock angle ranges we can see clearly, as we expect, that as the dipole tilts farther and farther toward the Sun, the cusp location moves farther equatorward.

Shape of the Magnetopause

The magnetopause locations in Figures 2 and 3 show little evidence for the indentation surrounding the polar cusp seen in inviscid models of the magnetopause shape (e.g., Mauel and Board, 1964; Speiser and Briggs, 1961, 1962). If there is any indentation, it must be very narrow, so it is difficult to observe. Moreover, it seems to move, and this motion is controlled by more than just the tilt angle of the dipole. The IMF clearly plays a role, as may other solar wind parameters. Although we cannot determine the detailed shape of the magnetopause near the cusp, we do have enough data to determine the approximate shape. In Figures 4a and 4b we plot all the magnetopause crossings in the GSM system. The grey curve is the magnetopause shape obtained at low latitudes and in the tail region from the empirical model of Perrin and Russell (1999b). The dark curve is the fit to the Hawkeye data. For these high-latitude data the average
shape is obtained by fitting the data points to a conic section \[ a e (1-e^2)(1+e \cos \theta) = c^2 \], where \( r \) is the geometric distance, \( \theta \) is the solar zenith angle (cosine of incidence), \( e \) is eccentricity, and \( r_e \) is the standoff distance of the magnetopause. For northward IMF the distance of the nose is 8.56 ± 0.10 \( R_E \), and the eccentricity is 0.73 ± 0.05. For both IMF directions the subauroral point is closer than that obtained for similar pressure by Pierrard and Russell [1993a]. Since Hayakawa does not cross the subauroral magnetopause, we do not know if this discrepancy represents a difference in the overall size of the magnetopause during the two epochs or a different shape of the magnetopause in the noon meridian and the equatorial plane. Comparing Figure 4a with Figure 4a, we find that as expected, the post-terminator tail region is wider for southward IMF than for northward IMF.

The polar cusp is by definition located poleward of the below-cusp crossings and equatorward of the above-cusp crossings. In the GSM system, for \( B_z \) > 0 the latitude of the equatorward point of the above the cusp crossings is about 77°, while for \( B_z < 0 \) it is about 74°. These are the lower limits of the polar cusp latitude. If we attempt to determine an average position of the cusp, it is about 82° for \( B_z > 0 \) and about 89° for \( B_z < 0 \). The cusp is swept back slightly further for northward IMF.

Neither Tsyganenko’s vacuum nor his empirical model includes an explicit IMF dependence, so we do not have guidance for the expected size of the IMF dependence. However, the size of the dependence observable is much smaller than the difference between these models and the observed positions. From Tsyganenko’s [1988b] vacuum model we would expect the polar cusp to be located at about 60°, and from his empirical model, the polar cusp latitude is even smaller. Thus the polar cusp latitude we obtain is much greater than that of Tsyganenko’s models. Clearly, the polar cusp is swept back from the vacuum location for both northward and southward IMF. However, we note that it is just as clearly swept back as much as Wats’s [1984] MHD model for northward IMF.

Figure 2. Magnetopause crossings for magnetopause clock angles within 22.9° of the noon meridian, for (a) northward and (b) southward IMF. Solid circles show crossings above the cusp and open circles below the cusp.

Figure 3. The dependence of the cusp location on dipole tilt angle: (a) near the noon meridian (high positional clock angles of 67.5° to 112.5°), and (b) at intermediate clock angles (45° to 67.5° and 112.5° to 135°). Circles are for \( B_z > 0 \), and squares are for \( B_z < 0 \).
Finally, we note that although we do not see evidence for an indentation of the magnetopause surrounding the polar cusp, we do see evidence for an enlargement of the cross section of the magnetopause behind the cusp. This is clearly present in both Figures 4a and 4b but is slightly larger for northward IMF. For northward IMF the intercept of the fitted curve with the terminator is $1.9 \pm 0.3 \, \text{R}_e$ for postcusp and $1.7 \pm 0.15 \, \text{R}_e$ for precusp. For southward IMF, $1.4 \pm 0.35 \, \text{R}_e$ for postcusp and $1.4 \pm 0.08 \, \text{R}_e$ for precusp. These differences indicate that the cusp is expanding. The solid symbols are magnetopause positions above the cusp, and open ones are below the cusp. The circles are for high clock angles, and the squares are for intermediate clock angles.

**GSM and SM Coordinates**

Usually, the GSM system is used for studying the magnetopause position, but during the day the polar cusp position will move back and forth in GSM coordinates as the dipole tilt angle changes. In order to remove the tilt angle effect, we would like to find a coordinate system that can provide all possible solutions for a fixed tilt angle. The solar magnetic (SM) coordinate system can be one of these possibilities, since the foot of the cusp is approximately fixed in this system, moving only about $4^\circ$ as the dipole tilt varies between $-35^\circ$ and $+35^\circ$ (Spyropoulos, 1990). Here the polar cusp is along the dipole direction. Figure 5 shows all the magnetopause crossings in the SM system. Figure 6a is for high clock angles and Figure 6b is for middle clock angles. Although in this system the polar cusp is nearly fixed relative to the Earth, we find that the cusp location is not nearly as fixed at the magnetopause. The comparison of Figure 5 with Figure 3 shows that the GSM system provides better separation of the region above the cusp from that below the cusp at all dipole tilt angles. Figure 6 shows all these data points in the SM system independent of tilt together with a fit of the shape for both northward and southward IMF. Again the cusp position is more...
Figure 6. Similar to Figure 4, but in the SM system.

Discussion and Conclusions

Observations with the Hawkeye spacecraft in the neighborhood of the polar cusp show that the polar cusp is swept back by the solar wind from its expected (in situ) location whether the IMF is northward or southward. As expected, the polar cusp location is controlled by the tilt of the dipole, so that it moves increasingly toward the Sun as the dipole tilts more toward the Sun. In the GSM system the lower limit of polar cusp latitude is about 77° for $B_z < 0$ and 74° for $B_z > 0$, showing that the cusp moves slightly toward the Sun for $B_z > 0$. While this is more than that found in in situ models, it is less than that found in MHD models. The magnetopause is about 5 Earth radii from the Earth behind the cusp than in front of it. This effect is slightly larger for northward IMF than for southward IMF. We do not know whether this enlargement of the cross section of the magnetosphere is gradual across the location of the cusp or occurs abruptly in the region where the field lines are swept back. We see no evidence for an indentation of the magnetopause near the cusp as is often drawn in cartoons of this region.

We find that the GSM system is better than the SM system in ordering magnetopause crossings at high latitudes. We expect this because both solar wind flow and the Earth's magnetic field jointly control the polar cusp. The extrapolated subsolar positions of the magnetopause that we obtain are significantly inside those obtained by Petrinec and Russell (1993a). Since solar wind data used to normalize the magnetopause position were obtained from the same IMF and instruments in both studies, we can attribute this to a difference in instrument calibration or a temporal change in solar wind properties. It is possible that the simple conic section used in these fits is a poor approximation to the shape of the boundary over the full three-dimensional surface. Thus when data are obtained primarily near the terminator plane at high latitudes, as here, the positions extrapolate poorly to the pole. In earlier work these fits were always dominated by low solar zenith angle and low-latitude data.

Finally we note that the overall size of the magnetopause cross section does not vary much with the direction of the IMF when studied near the terminator plane. This observation is consistent with studies at low latitudes and occurs because the tail increases in width for southward IMF when the dayside shrinks and vice versa for northward IMF. The terminator plane is roughly the dividing line between these variations.

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