

Polar magnetopause crossings of May 29, 1996: Implications for magnetic field modeling

Andrew L. Urquhart, Patricia H. Reiff, Frank R. Toffoletto,
Thomas W. Hill, and Todd R. Konkel

Department of Space Physics and Astronomy, Rice University, Houston, Texas

Christopher T. Russell and Guan Le

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

Sergey P. Savin and Stanislav A. Romanov

Space Research Institute, Russian Academy of Sciences, Moscow, Russia

Abstract. During 1996, the magnetometer and particle instruments on NASA's Polar spacecraft detected several apparent magnetopause crossings. In contrast, with a geocentric apogee of only $9 R_E$ over the northern pole, this spacecraft was not expected to leave the magnetosphere. We have investigated the modifications that are required in existing magnetospheric magnetic field models in order to account for these observations. In order to match the observed particle distributions (reported elsewhere,) this model includes northward-IMF reconnection. For the event of May 29, 1996, unusual magnetic and particle observations began at an altitude of $5 R_E$ while the spacecraft was sunward of the expected northern cusp position. Using a cylindrically symmetric magnetopause, we are able to reproduce the measured field reasonably well but with problems in the timing of the boundary crossings. The crossing times are much improved by making an adjustment in the spacecraft position which could arise either from motion of the boundary or an indentation in the magnetopause at the cusp. The results from this model are compared against results from the analytic open-magnetosphere *Toffoletto and Hill* [1993] model and the empirical *Tsyganenko* [1996] model; significant improvement over both prior models is shown. This improvement is shown not only with respect to data from Polar but also with respect to data from the Interball-Tail spacecraft. The model indicates that the Polar spacecraft encountered regions of "overdraped lobe" field lines that connect to the southern polar cap but exit the magnetosphere through the northern cusp.

1. Introduction

The NASA Polar spacecraft was launched on February 24, 1996, from Space Launch Complex 6, Vandenberg Air Force Base, California, and was soon thereafter transferred into its objective $2 R_E \times 9 R_E$, 90° -inclination orbit with apogee over the high-latitude northern hemisphere [*Acuña et al.*, 1995]. Shortly after the beginning of normal science operations the Polar Magnetic Fields Experiment [*Russell et al.*, 1995], along with Polar's other in situ plasma instruments, detected a series of unusual events that displayed signatures of magnetopause crossings into the magnetosheath; the longest, cleanest event was observed between approx-

imately 0400 and 0700 UT on May 29, 1996, and was noted in magnetic fields by *Russell et al.* [1997] and in energetic particles by *Grande et al.* [1996]. During this particular event, the spacecraft location was such that (even considering the enhanced solar wind pressure observed by Wind) Polar was expected to still be inside the magnetosphere [*Zhou and Russell*, 1997]. We have attempted to explain this event using a modification of the *Toffoletto et al.* [1994] procedure to model cusp reconnection in an overdraped-lobe geometry [*Russell*, 1972; *Crooker*, 1979]. The timing of this event proved to be the most difficult property to explain, especially since it ended more than an hour before Polar reached the apogee of its 18-hour orbit. The observed magnetic fields could be reproduced only by having the spacecraft cross the magnetopause current sheet twice during the ascent to apogee. In order to match the observed boundary timing and the associ-

Copyright 1998 by the American Geophysical Union.

Paper number 98JA00012.
0148-0227/98/98JA-00012\$09.00

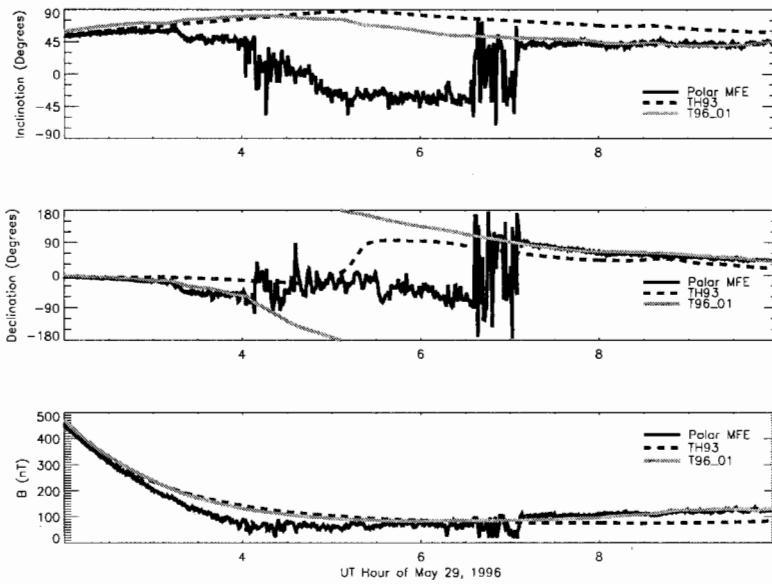


Figure 1. Polar magnetometer observations for the May 29, 1996, event compared with an analytic model (TH93) and an empirical model (T96_01). The event occurred between 0300 and 0700 UT.

ated positions, it has been necessary to approximate the effects of a magnetopause indentation in the cusp region, as proposed by *Choe et al.* [1973]. *Haerendel and Paschmann* [1975] inferred similar cusp magnetopause indentations to explain a portion of the Heos 2 observations. In order to verify the validity of this model, we have successfully compared its predictions to observations from the Interball-Tail MFI-M magnetometer experiment [*Klimov et al.*, 1997].

2. Observations

Since under normal conditions the dipolar component dominates the geomagnetic field throughout the 2 – 9 R_E (geocentric) distance range accessible to Polar, the inclination-declination coordinate system [*Mead and Cahill*, 1967; *Russell*, 1971] is arguably the most natural coordinate system for the presentation and comparison of Polar MFE observations. In this system, the inclination (or dip angle) is the angle between the magnetic field vector and the horizontal plane (the plane normal to the local geocentric radius vector.) Conventionally, this angle is positive down.

This system's second coordinate, the declination, is the angle between the magnetic field's horizontal component and the horizontal direction toward the dipolar north pole. For a pure dipole field, the declination is strictly zero everywhere; nondipolar distortions give rise to nonzero declinations. Conventionally, the declination is positive eastward and negative westward. The description of the field vector in this system is completed by the field magnitude.

Figure 1 shows the ambient magnetic field measured by Polar in comparison with the predictions of both

the TH93 [*Toffoletto and Hill*, 1993] analytic magnetosphere model and the T96_01 [*Tsyganenko*, 1996] empirical magnetosphere model. Figure 2 shows, on both global and cusp-local scales, the TH93 field lines traced from Polar's position; Figure 3 shows the analogous T96_01 field lines. These three-dimensional field lines, traced every 100 spacecraft spins, are shown projected into a plane which approximately contains the orbit. This plane lies halfway between the noon-midnight and dawn-dusk planes so that the view is from the dayside dusk quadrant. Both models were driven by the appropriate data from the SWE [*Ogilvie et al.*, 1995] and MFI [*Lepping et al.*, 1995] experiments on the Wind spacecraft.

At the beginning and end of the interval shown, the data agree very well with the empirical T96_01 model. However, between approximately 0300 and 0700 UT, the magnetic field departs significantly from T96_01. This deviation is especially dramatic in the direction of the field. A little after 0300 UT the measured field slowly rotates upward through the horizontal; during this rotation the inclinations ramp down from about $+60^\circ$ to about -30° at about 0500 UT. After 0500 UT, the field inclination then remains effectively steady until about 0630 UT, at which point it begins a large amplitude bimodal oscillation until a little after 0700 UT. Given the spacecraft location and field magnitude, this translates to a variation in the vertical component from -70 to $+50$ nT.

The observed magnetic field declination also deviates significantly from the models; it turns westward to near -45° a little after 0300 UT, rotates back to just west of 0° (but unsteady) between 0400 and 0530 UT, and then jumps back to -45° until 0630 UT. During this pe-

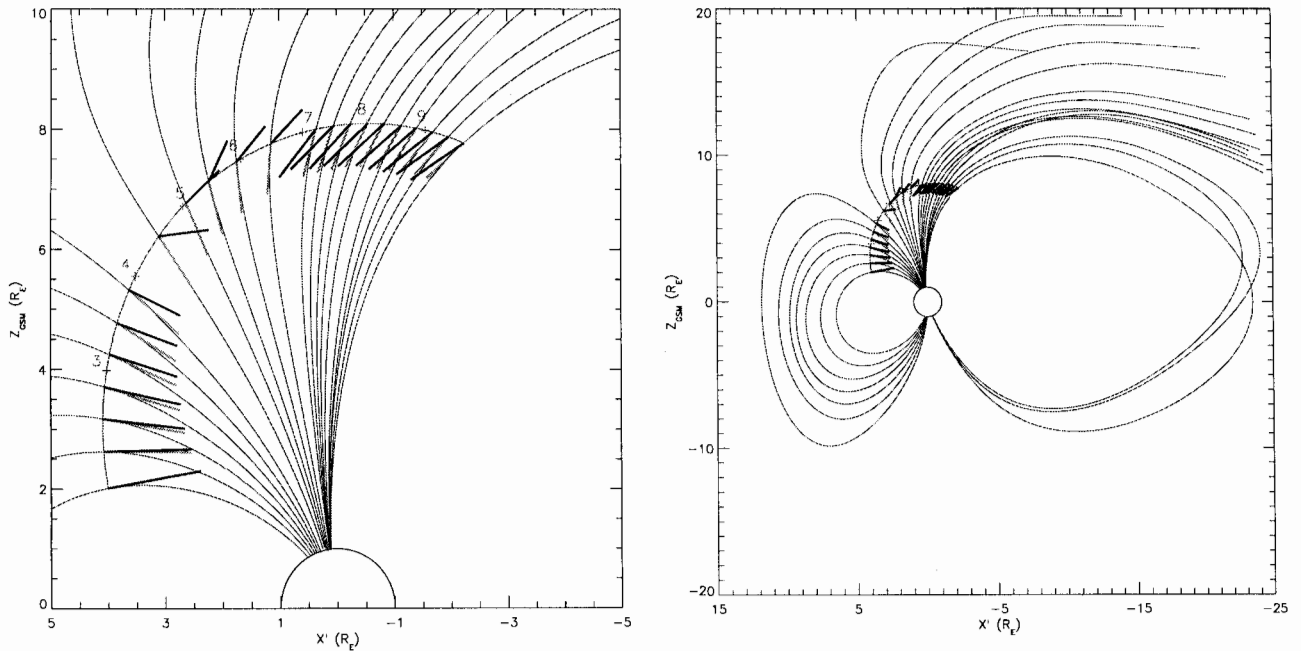


Figure 2. TH93 field lines passing through the Polar spacecraft position, traced every 100 spacecraft spins. The positive X' axis makes a 45° angle with the positive X_{GSM} and negative Y_{GSM} axes, so that the spacecraft orbit lies nearly in the $X'-Z_{GSM}$ plane. The projection of the orbital track is shown with plus symbols at each UT-hour boundary. The associated UT-hour is marked near each such symbol in the magnified view. Dark vectors give the observed field vector, and light vectors give the model field vector; both vector sets are logarithmically scaled (so that $10 \text{ nT} = 1 R_E$) and then projected into the plane of the paper.

riod, T96.01 turns from northwest through west, south, east, and then to northeast. The observed declination, like the inclination, oscillates through the interval 0630-0700 UT. This oscillation suggests a possible alternation between two states as could happen if the spacecraft crossed a magnetopause multiple times.

This event's signature is far less dramatic in the magnetic field intensity, but nonetheless a signature is present. As Polar rises from perigee at the beginning of the interval shown, both T96.01 and TH93 overpredict the observed magnetic field intensity. However, closer to apogee after 0830 UT, the T96.01 magnetic field inten-

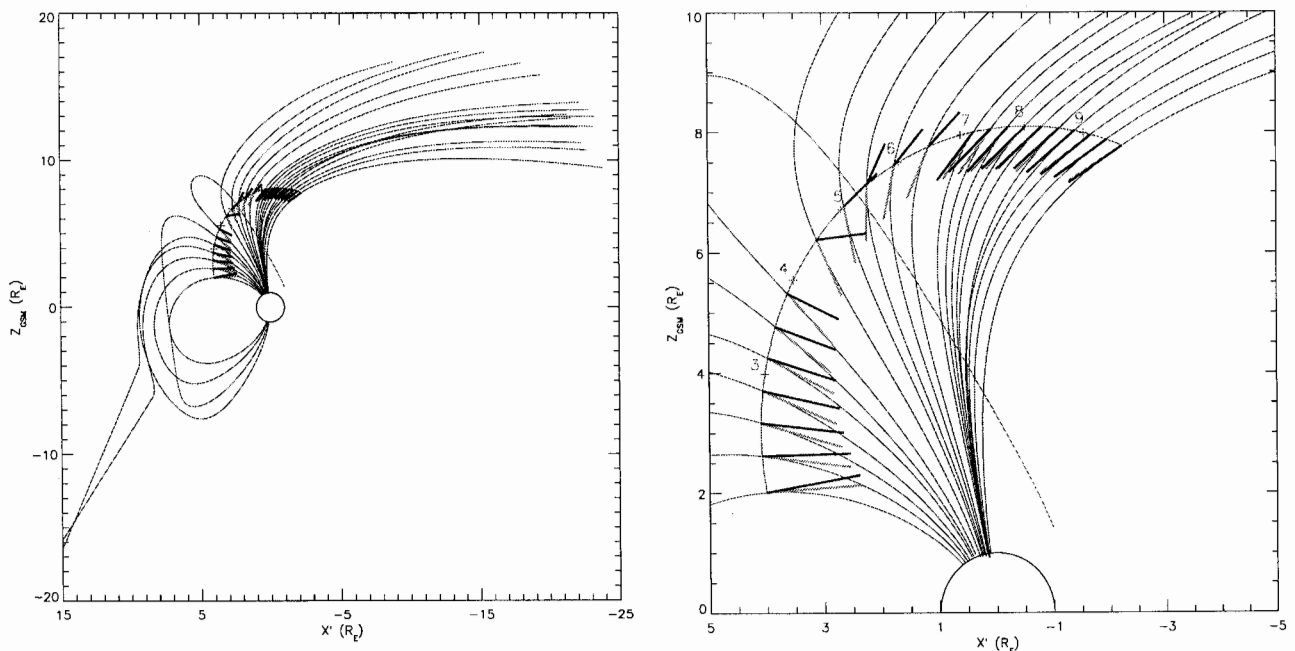


Figure 3. T96.01 field lines, in the same format as Figure 2.

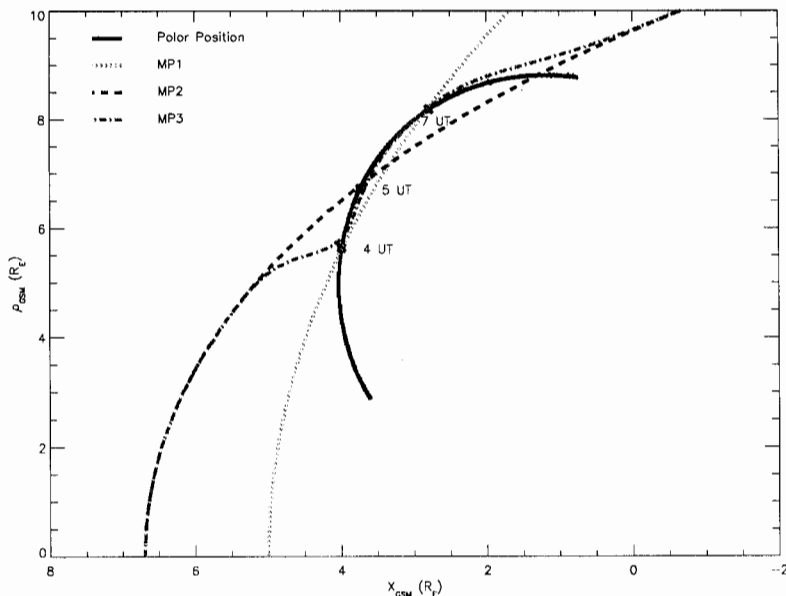


Figure 4. Polar spacecraft GSM position compared with possible magnetopause locations: MP1, smooth magnetopause ($x_0 = 5.0 R_E$) with crossings at ends of observed event interval; MP2, best-fit smooth magnetopause with reasonable standoff distance ($x_0 = 6.7 R_E$); MP3, MP2 perturbed so that magnetopause crossings correspond to ends of observed event interval. N.B., MP3 is cylindrically asymmetric, and orbit is nonplanar in GSM system; the perturbed magnetopause is shown in a cut which changes in θ with the spacecraft.

sity agrees well with the observations. In the interval 0300 to 0700 UT, the observed magnetic field intensity is generally below the model predictions. Again, the magnetic field intensity oscillates between 0630 and 0700 UT. After 0700 UT, T96.01 initially slightly underpredicts the observations. This disagreement lessens to insignificance by 0830 UT. TH93 consistently underpredicts the observed magnetic field intensity throughout the entire postevent interval.

At first glance, this event has the appearance of a spacecraft crossing into the magnetosheath; in support of this viewpoint, the magnetic field oscillations between 0630 and 0700 UT have the appearance of a magnetopause crossing with multiple actual magnetopause intercepts. Taking the spacecraft position into account complicates this interpretation: the event occurs not at apogee but on the ascending part of the orbit (see Figures 2, 3, and 4). On May 29, 1996, this portion of the orbit was sunward of the Earth near the noon-midnight plane. Geodipole tilts during this event ranged between 11° and 13° ; the diurnal minimum tilt of 11° occurred near 0443 UT.

3. Modeling

In order to simulate this event, we used the procedure of *Toffoletto et al.* [1994] with a cylindrically symmetric magnetopause of the form $\rho = \rho_0 \sqrt{(x - x_0)/(x - b)}$ where ρ is the magnetopause radius perpendicular to the X axis, ρ_0 is the asymptotic tail radius, x_0 is the standoff distance at the subsolar point, and b is a parameter controlling the bluntness of the magnetopause.

We then rotated the magnetopause interconnection field by approximately 180° , with the exact angle dependent on the clock angle of the interplanetary magnetic field (IMF), to allow the effects of merging with a northward IMF [Russell, 1972; Crooker, 1979]. The magnetosheath flow and fields were calculated using the procedures of *Spreiter and Stahara* [1980].

After testing the model with various assumed magnetopause parameters, we concluded that the observations could be reproduced only by allowing the spacecraft to cross the magnetopause into the magnetosheath flow. This agrees with the magnetopause signature assumed by *Haerendel and Paschmann* [1975] and *Paschmann et al.* [1976], except that those studies place the magnetopause at the innermost magnetic field reversal; as a consequence of Polar's orbit and the observed magnetic signature, we must place the magnetopause near both the innermost and outermost magnetic field reversals. Considering this, Figure 4 shows the spacecraft position with respect to the several possible magnetopauses. Also included are points marking the beginning and end of the interesting interval. Fitting a smooth magnetopause through these points proved quite difficult. Allowing the spacecraft to leave the magnetosphere at a geocentric distance in the range $6 - 7 R_E$ and then to reenter at apogee required a nose standoff distance well inside geosynchronous orbit (MP1 of Figure 4). This is inconsistent with the relevant solar wind observations which indicate magnetospheric compression, but only to 81% of the usual radius [Russell et al., 1996].

In order to model this event, we first set the magnetopause standoff distance x_0 to $6.7 R_E$ in accordance

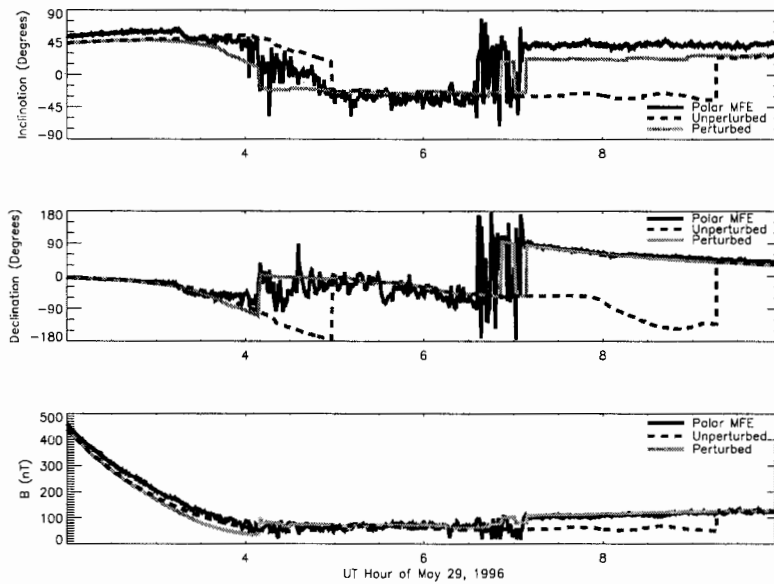


Figure 5. Magnetic fields from our new model, unperturbed and perturbed, in comparison with Polar MFE observations for the May 29, 1996, event.

with the observed solar wind dynamic pressure. The asymptotic tail radius ρ_0 was then set to $22 R_E$ so that the model magnetic field intensity matched the observed intensity during the later (more tailward) part of the data interval. Finally, the bluntness parameter b was set to $35 R_E$ so that the Polar orbit passed slightly outside the magnetopause beginning near 0500 UT. We then employed the *Toffoletto et al.* [1994] procedure with an interconnection field sufficient to generate a 30 kV reverse reconnection potential. Figure 5 includes the results of this “unperturbed” model, whose magnetopause is MP2 in Figure 4. These results show significant improvement over the predictions shown in Figure 1.

As expected from the magnetopause geometries shown in Figure 4, the symmetric magnetopause model fails to predict the timing of the Polar MFE observations. Not surprisingly, the predicted event start and end times (0500 and 0915 UT) coincide roughly with the unperturbed model magnetopause crossings. Forcing event interval coincidence between the observations and a symmetric magnetopause model would require an unacceptable magnetopause compression into $5.0 R_E$ (MP1 in Figure 4).

There is another option: several theoretical magnetopause models include an indentation in the cusp region [Beard, 1960, 1962; Spreiter and Briggs, 1962; Midgley and Davis, 1962; Slutz, 1962; Beard and Jenkins, 1962; Mead and Beard, 1964; Mead, 1964; Midgley, 1964; Baker et al., 1964; Olson, 1969; Choe et al., 1973]. Observational results to date have reached mixed conclusions as to the existence of magnetopause indentation at the cusp. Some studies, such as *Haerendel and Paschmann* [1975], *Paschmann et al.* [1976], and *Haerendel et al.* [1978], have inferred the presence of a significant plasma population in the outer cusp which they call the “entry layer.” Current sheets are observed

on both the inner and outer edges of this entry layer. The innermost current sheet arises because of diamagnetic currents on the inner edge of the entry layer. If one identifies this inner current sheet with the magnetopause, then a significant magnetopause indentation is required. We must note here that other studies (such as that of *Zhou and Russell* [1997]) have failed to detect an indented cusp, although Zhou and Russell did detect an enlargement of the magnetopause tailward of the cusp. This enlargement is consistent with the theoretical magnetopause models that include a magnetotail.

Direct inclusion of an indented magnetopause current sheet near the cusp breaks the cylindrical symmetry required by both the *Spreiter and Stahara* [1980] magnetosheath procedures and the present implementation of the *Toffoletto et al.* [1994] Chapman-Ferraro solver. The present *Toffoletto et al.* [1994] procedure also allows only the Chapman-Ferraro current near the magnetopause. Future implementations of the *Toffoletto et al.* procedure will need to include an additional diamagnetic current system. Until such an implementation becomes available, we have approximated the effect by sampling the *Spreiter and Stahara* and *Toffoletto et al.* model fields at virtual spacecraft positions related to the real spacecraft positions. Each virtual position was displaced from its associated real position so that the pair remained on the same geocentric radius vector; the indentation relative to the cylindrically symmetric *Spreiter and Stahara* and *Toffoletto et al.* magnetopause determined the magnitude of the displacement. We tested the model using the *Choe et al.* [1973] magnetopause to determine this displacement. We found that their magnetopause indents too deeply near the cusp; for the solar wind conditions during this event, it left the Polar vehicle in the solar wind for several hours longer than was actually observed. Thus we suspect that the prob-

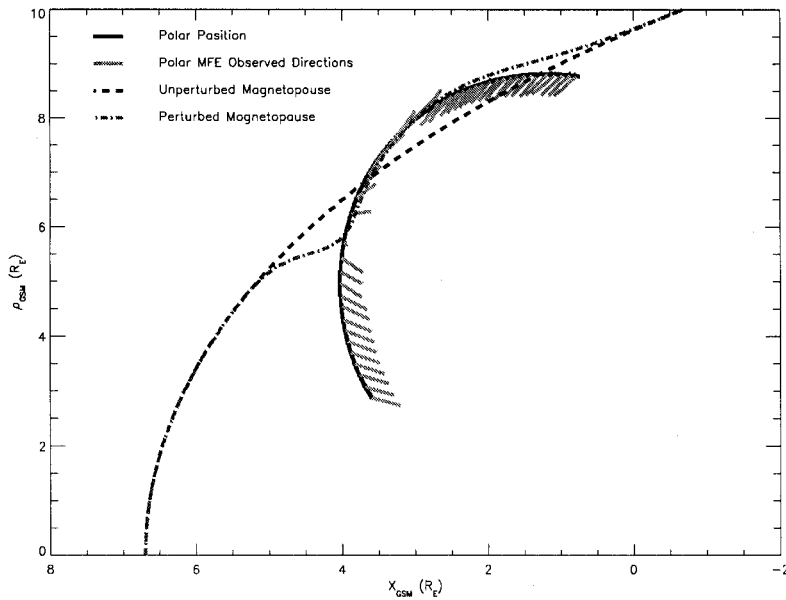


Figure 6. Polar MFE vectors from the spacecraft position compared with the inferred magnetopause. Like MP3 in Figure 4, the perturbed magnetopause is shown in a cut which changes in θ with the spacecraft.

lem is caused by the lack of a second current sheet and not an indentation in the exterior magnetopause.

In absence of a two-current sheet magnetopause, we have used an ad hoc conceptual perturbation of the Toffoletto et al. current layer. This perturbation, based on the GSM angles $\lambda = \cos^{-1}(X_{GSM}/R_{GSM})$ and $\theta = \tan^{-1}(Y_{GSM}/Z_{GSM})$, has the form:

$$\left(\frac{R}{R_0}\right)^{-1} = 1 + \left\{ \sum_{n=1,2} a_n \exp \left[- \left(\frac{\lambda - \lambda_n}{w_n} \right)^2 \right] \right\} \cos^2 \theta$$

where R is the new magnetopause radius, R_0 is the smooth-magnetopause radius, and R_{GSM} is the radial distance of the spacecraft from the center of the Earth. The free parameters have been adjusted so that the spacecraft intersects the magnetopause at the approximate beginning and end of the observed event. Such intersections correspond approximately, but not exactly, with the beginning and end of the event signature. This perturbation has been implemented not by changing the magnetic field, but by querying the magnetic field model at $(R/R_0) \times R_{GSM}$ instead of at R_{GSM} . The magnetopause used for this purpose, MP3 in Figure 4, has perturbation parameters $a_1 = 0.07$, $\lambda_1 = 55^\circ$, $w_1 = 6^\circ$, $a_2 = -0.06$, $\lambda_2 = 74^\circ$, $w_2 = 10^\circ$. This procedure is not intended to represent a physically self-consistent field perturbation (for example, it does not satisfy $\nabla \cdot B = 0$), but rather it indicates qualitatively the type of boundary perturbations that would be required to explain the observations. We assume that nature could produce a qualitatively similar boundary perturbation without violating $\nabla \cdot B = 0$. With this in mind, we find that the perturbed boundary increases observational agreement dramatically as shown in Figure 5 (the trace labeled

"Perturbed.") This increase is such that it highlights the two primary remaining disagreements: failure to reproduce the field signature in the magnetosphere exit region and a general underprediction of the field inclination.

The first disagreement occurs in association with the first (exiting) magnetopause crossing. Here the Polar MFE inclination shows a gentle ramp over an hour of UT. The model is unable to reproduce this ramp; instead it predicts a sharp transition where the spacecraft crosses the model magnetopause current layer. The model also includes a sharp magnetic field intensification at the current sheet crossing; the observations include no such feature anywhere near the beginning of the event. The model employs a thin magnetopause, while the observations suggest that the exit magnetopause may be a diffuse structure – possibly as a result of interconnection between the magnetospheric field and the IMF. Another contributing factor may be turbulent mixing driven by the magnetosheath flow interacting with the cusp indentation. This interaction could generate an entry layer as inferred by *Haerendel and Paschmann* [1975]. Note that Haerendel and Paschmann found distinctly sharp magnetopauses on the sunward side of the cusp where we observe a diffuse structure.

In contrast with the first magnetopause crossing, the second observed (reentry) magnetopause crossing is reproduced well by the model. The model here gives a single cycle of large amplitude bimodal oscillation in the field; the phasing of this cycle is in good agreement with the observed oscillation phasing. Small oscillations of the actual magnetopause position probably account for the multiple cycle of the observed field oscillation,

in contrast to the single cycle predicted by the static model.

The second disagreement, underprediction of the inclination, most likely results from the ad hoc nature of the magnetopause perturbation method. As shown in Figure 6, the observed magnetic field vectors are nearly tangent to the perturbed magnetopause, while the model field vectors (as expected) are more nearly tangent to the unperturbed magnetopause from which they were calculated. Correction of this error will re-

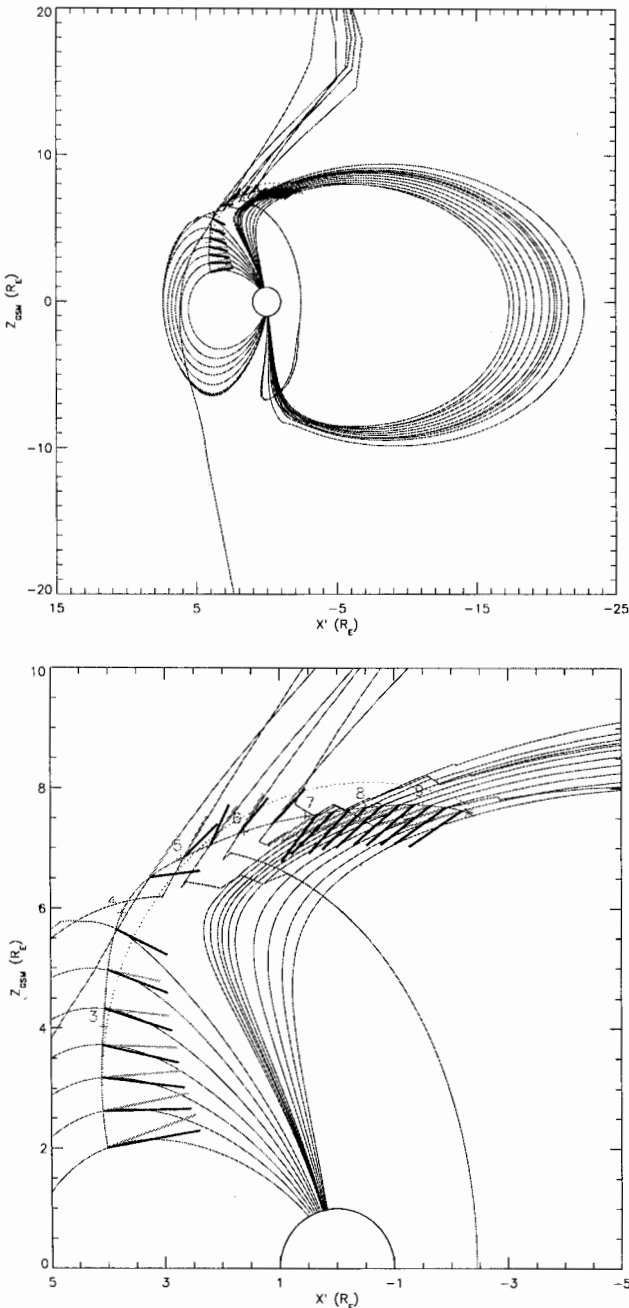


Figure 7. Field lines of our new model passing through the perturbed Polar spacecraft position. The format and view are the same as in Figures 2 and 3, with an additional dotted line representing the unperturbed Polar positions.

quire the solution of the magnetic field within a three-dimensional asymmetric magnetopause. Methods to generate such solutions are still under development.

The model field lines passing through the "perturbed" spacecraft position are shown in Figure 7. The lines corresponding to the event interval, plotted separately in Figure 8, have the overdraped geometry suggested by *Russell* [1972] and *Crooker* [1979] in that they pass through the northern cusp magnetopause but connect to the southern ionosphere. These overdraped field lines form part of both the dayside and nightside magnetosphere; the field lines that appear to pass near the Earth actually pass along the dusk flank of the magnetosphere. Figures 7 and 8 also show field lines that are completely disconnected from the Earth. Our experience in developing this model indicates that the cusp region contains only a thin layer of "open" field lines near the magnetopause. The unconnected field lines may have thus appeared through overperturbation of the spacecraft position; if real, they should be marked by dropouts of magnetospheric particles from the Polar particle detectors.

4. Verification

Having constructed a model to explain the Polar observations, we found that Interball-Tail had crossed the magnetopause at nearly the same time but northward and downward from Polar. Knowing only that Interball had good data, but knowing nothing more, we then used our model along with TH93 and T96_01 to predict the magnetic fields observed by the Interball spacecraft. The combined results are shown in Figure 9. Although lacking perfect agreement with the observations, our new model significantly outperformed both the TH93 and T96_01 models, especially at lower altitudes. (Note that Interball-Tail has a high apogee so that after 0800 UT it is certainly in the solar wind where all of the models perform equivalently.) Our model magnetopause near 0300 UT is closest to the observed magnetopause near 0315 UT, and the general pattern of our field directions is closest to the observed pattern of field directions. The timing of boundaries between different field directions are slightly inaccurate; however, this should not detract from the superior pattern prediction from this new model. Note that the superior pattern prediction exists even with the unperturbed model variant which includes only cusp reconnection and current sheet indentation at the cusp. This variant shows degradation in the boundary timings but is still better than the T96_01 and TH93 models.

5. Conclusions

The altitude at which Polar encountered the magnetosheath plasma, in conjunction with the solar wind conditions observed on the Wind satellite, argues for a dual current sheet with the innermost current at the

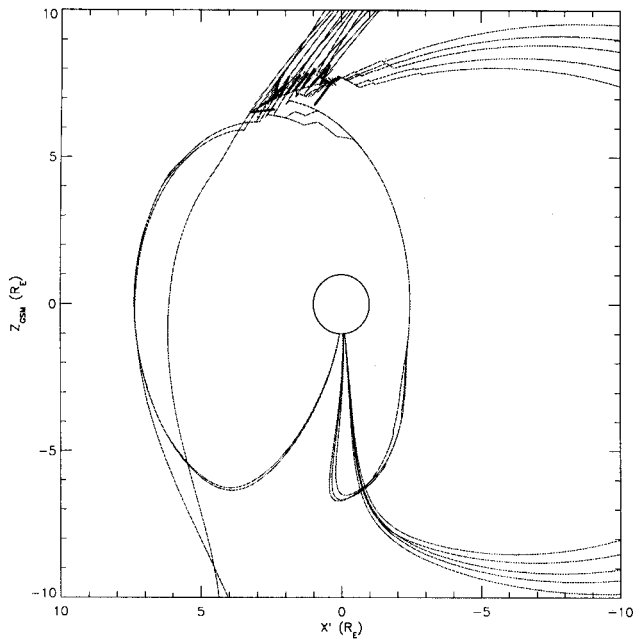


Figure 8. Selected field lines from the event times in Figure 7, shown every 50 spacecraft spins.

inner edge of the entry layer. Future TH93-derivative models will include an entry layer current; for the interim we have used a single layer which has been perturbed to approximate the entry-layer effect.

Employment of an ad hoc Gaussian-shaped perturbation of the spacecraft position allows the prediction of magnetic fields that agree well with the Polar MFE measurements. This perturbation simulates an inward indentation of the magnetopause current sheet near the cusp as well as a magnetopause expansion tailward of the cusp. The postcusp expansion agrees with the observations of *Zhou and Russell* [1997]; our modeling of this phenomenon is imperfect, as indicated by our un-

derprediction of post-cusp field inclinations. The inclusion of a cusp indentation improves agreement with the Interball-Tail observations; however, even without the perturbation this model predicts the Interball-Tail observations better than do the prior models. The topology of this new model suggests that Polar intersected field lines that were open through the northern cusp magnetopause and overdrafted to the southern ionosphere.

Very few cusp-magnetosheath transits of this type have been observed. Indeed, the Heos 2 event of June 2, 1973 [*Haerendel and Paschmann*, 1975; *Paschmann et al.*, 1976] may be the next best example. Several selection factors work against the observation of such events. Prime among these is the fact that the high-altitude polar magnetosphere has remained relatively unexplored; the database used to build empirical field models such as T96_01 contained high-altitude polar magnetospheric data only from the Heos 2 mission [*Fairfield et al.*, 1994]. For Polar, the spacecraft's low altitude with respect to nominal magnetopause standoff distances requires unusually high solar wind pressures before an indentation can be observed. The motion of the Earth-Sun line with respect to the spacecraft's inertial orbital plane represents another deselection factor: the spacecraft orbit approaches the cusp only during a small portion of each year. The Heos 2 data suggest a final deselection factor: *Haerendel and Paschmann* and *Paschmann et al.* infer a smooth magnetopause for several Heos 2 passes (especially May 18, 1973) instead of the indented magnetopause needed for both the Heos 2 pass of June 2, 1973 and the Polar pass of May 29, 1996. Since the Interball-Tail orbit reaches a higher apogee, some of the deselection factors become less important and magnetopause indentation signatures are observed more often with that spacecraft [*Savin et al.*, 1997].

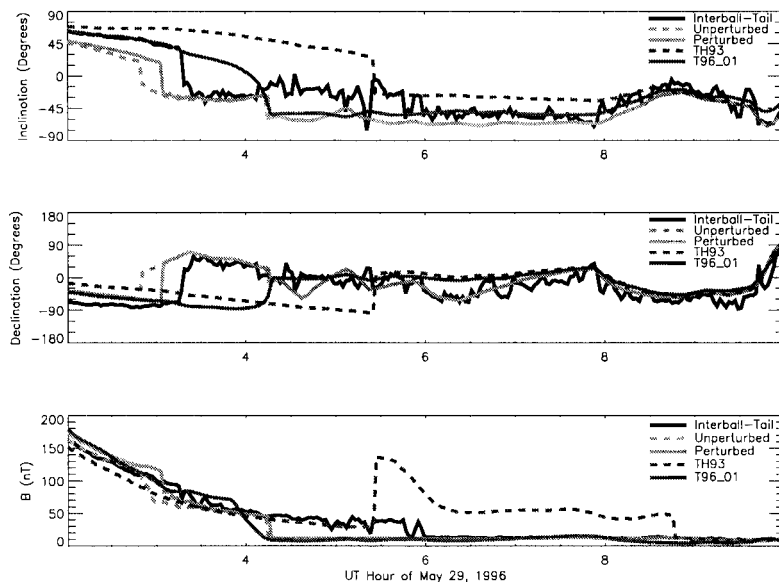


Figure 9. Magnetic fields from our new model, perturbed and unperturbed, compared with Interball-Tail observations. TH93 and T96_01 are also shown for comparison.

The observations from Polar on this day suggest that the magnetopause probably does have a cusp current sheet indentation at least some of the time, but that this indentation may be smaller than predicted by *Choe et al.* [1973] and preceding studies. We also find an expanded magnetopause tailward of the indentation. Additionally, we find that the Polar magnetic field measurements are consistent with a cusp interconnection field generated by reconnection of the magnetospheric field with a strongly northward IMF. Such an interconnection field, when actually present, can be reasonably expected to yield overdraped field lines that cross the magnetopause surface in one hemisphere but connect to the ionosphere in the opposite hemisphere.

Acknowledgments. The authors wish to thank K. W. Ogilvie, R. P. Lepping, and their respective instrument teams for providing the Wind data used to drive the models, A. Petrukovich for processing the Interball-Tail MFI-M key parameter data, and N. A. Tsyganenko for use of his GEOPACK coordinate transformation library. This work has been supported by NASA under grants NAG5-3216, NGT-53182, and NGT5-50199; and by NSF under grant ATM-9501898.

The Editor thanks two referees for their assistance in evaluating this paper.

References

- Acuña, M. H., K. W. Ogilvie, D. N. Baker, S. A. Curtis, D. H. Fairfield, and W. H. Mish, The global geospace science program and its investigations, in *The Global Geospace Mission*, edited by C. T. Russell, pp. 5-21, Kluwer Acad., Norwell, Mass., 1995.
- Baker, J. C., D. B. Beard, and J. C. Young, Self-consistent method for determining the boundary shape between a plasma and a magnetic field, *Phys. Fluids*, **7**, 504-510, 1964.
- Beard, D. B., The interaction of the terrestrial magnetic field with the solar corpuscular radiation, *J. Geophys. Res.*, **65**, 3559-3568, 1960.
- Beard, D. B., The interaction of the terrestrial magnetic field with the solar corpuscular radiation, 2, Second-order approximation, *J. Geophys. Res.*, **67**, 477-483, 1962.
- Beard, D. B., and E. B. Jenkins, Correction to the second approximation calculation of the geomagnetic field, solar wind interface, *J. Geophys. Res.*, **67**, 4895-4896, 1962.
- Choe, J. Y., D. B. Beard, and E. C. Sullivan, Precise calculation of the magnetosphere surface for a tilted dipole, *Planet. Space Sci.*, **21**, 485-498, 1973.
- Crooker, N. U., Dayside merging and cusp geometry, *J. Geophys. Res.*, **84**, 951-959, 1979.
- Fairfield, D. H., N. A. Tsyganenko, A. V. Usmanov, and M. V. Malkov, A large magnetosphere magnetic field database, *J. Geophys. Res.*, **99**, 11,319-11,326, 1994.
- Grande, M., J. Fennell, S. Livi, B. Kellett, C. Perry, P. Anderson, J. Roeder, H. Spence, T. Fritz, and B. Wilken, Observations of the mid-altitude magnetosheath during a persistent northward IMF condition: Polar CAMMICE observations, *Geophys. Res. Lett.*, **24**, 1475-1478, 1997.
- Haerendel, G., and G. Paschmann, Entry of solar wind plasma into the magnetosphere, in *Physics of the Hot Plasma in the Magnetosphere*, edited by B. Hultqvist and L. Stenflo, pp. 23-43, Plenum, New York, 1975.
- Haerendel, G., G. Paschmann, N. Sckopke, H. Rosenbauer, and P. C. Hedgecock, The frontside boundary layer of the magnetosphere and the problem of reconnection, *J. Geophys. Res.*, **83**, 3195-3216, 1978.
- Klimov, S., et al., ASPI experiment: Measurements of fields and waves onboard the Interball-1 spacecraft, *Ann. Geophys.*, **15**, 514-527, 1997.
- Lepping, R. P., et al., The Wind magnetic field investigation, in *The Global Geospace Mission*, edited by C. T. Russell, pp. 207-229, Kluwer Acad., Norwell, Mass., 1995.
- Mead, G. D., Deformation of the geomagnetic field by the solar wind, *J. Geophys. Res.*, **69**, 1181-1195, 1964.
- Mead, G. D., and D. B. Beard, Shape of the geomagnetic field solar wind boundary, *J. Geophys. Res.*, **69**, 1169-1179, 1964.
- Mead, G. D., and L. J. Cahill, Explorer 12 measurements of the distortion of the geomagnetic field, *J. Geophys. Res.*, **72**, 2737-2748, 1967.
- Midgley, J. E., Perturbation of the geomagnetic field - A spherical harmonic expansion, *J. Geophys. Res.*, **69**, 1197-1200, 1964.
- Midgley, J. E., and L. Davis, Computation of the bounding surface of a dipole field in a plasma by a moment technique, *J. Geophys. Res.*, **67**, 499-504, 1962.
- Ogilvie, K. W., et al., SWE, A comprehensive plasma instrument for the Wind spacecraft, in *The Global Geospace Mission*, edited by C. T. Russell, pp. 55-77, Kluwer Acad., Norwell, Mass., 1995.
- Olson, W. P., The shape of the tilted magnetopause, *J. Geophys. Res.*, **74**, 5642-5651, 1969.
- Paschmann, G., G. Haerendel, N. Sckopke, H. Rosenbauer, and P. C. Hedgecock, Plasma and magnetic field characteristics of the distant polar cusp near local noon: The entry layer, *J. Geophys. Res.*, **81**, 2883-2899, 1976.
- Russell, C. T., Geophysical coordinate transformations, *Cosmic Electrodyn.*, **2**, 184-196, 1971.
- Russell, C. T., The configuration of the magnetosphere, in *Critical Problems of Magnetospheric Physics, Proceedings of the Joint COSPAR/IAGA/URSI Symposium*, edited by E. R. Dyer, pp. 1-16, IUCSTP Sec., Washington, D.C., 1972.
- Russell, C. T., R. C. Snare, J. D. Means, D. Pierce, D. Dearborn, M. Larson, G. Barr, and G. Le, The GGS/Polar magnetic fields investigation, in *The Global Geospace Mission*, edited by C. T. Russell, pp. 563-582, Kluwer Acad., Norwell, Mass., 1995.
- Russell, C. T., G. Le, X.-W. Zhou, P. H. Reiff, J. G. Luhmann, C. A. Cattell, R. L. McPherron, and M. Ashour-Abdalla, Initial results from the Polar magnetic fields investigation, *Adv. Space Res.*, **20**, 833-839, 1997.
- Savin, S. P., et al., Interball Tail Probe measurements in outer cusp and boundary layers, in *Geophysical Monograph Series*, edited by J. Horwitz, AGU, Washington, D.C., in press, 1998.
- Slutz, R. J., The shape of the geomagnetic field boundary under uniform external pressure, *J. Geophys. Res.*, **67**, 505-513, 1962.
- Spreiter, J. R., and B. R. Briggs, Theoretical determination of the form of the boundary of the solar corpuscular stream produced by interaction with the magnetic dipole field of the Earth, *J. Geophys. Res.*, **67**, 37-51, 1962.
- Spreiter, J. R., and S. S. Stahara, A new predictive model for determining solar wind-terrestrial planet interactions, *J. Geophys. Res.*, **85**, 6769-6777, 1980.
- Toffoletto, F. R., and T. W. Hill, A nonsingular model of the open magnetosphere, *J. Geophys. Res.*, **98**, 1339-1344, 1993.
- Toffoletto, F. R., R. V. Hilmer, T. W. Hill, and G.-H. Voigt, Solution of the Chapman-Ferraro problem with an arbitrary magnetopause, *Geophys. Res. Lett.*, **21**, 621-624, 1994.

Tsyganenko, N. A., Effects of the solar wind conditions on the global magnetospheric configuration as deduced from data-based field models, in *Proceedings of the ICS-3 Conference on Substorms, Eur. Space Agency Spec. Publ., ESA SP-389*, 181-185, 1996.

Zhou, X.-W., and C. T. Russell, The location of the high-latitude polar cusp and the shape of the surrounding magnetopause, *J. Geophys. Res.*, *102*, 105-110, 1997.

T. W. Hill, T. R. Konkell, P. H. Reiff, F. R. Toffoletto, A. L. Urquhart, Department of Space Physics and Astronomy, MS 108, Rice University, 6100 Main Street, Houston, TX 77005. (e-mail: hill@rice.edu; zwieback@space.rice.edu; reiff@rice.edu; toffo@rice.edu; urquhart@rice.edu)

G. Le and C. T. Russell, Institute of Geophysics and Planetary Physics, 6877 Slichter Hall, University of California, Los Angeles, CA 90095-1567. (email: guan@igpp.ucla.edu; ctrussell@igpp.ucla.edu)

S. A. Romanov and S. P. Savin, Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, Moscow 117810, Russia. (email: sromanov@vmcom.lz.space.ru; ssavin@vm1.iki.rssi.ru)

(Received June 16, 1997; revised December 22, 1997; accepted December 29, 1997.)