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PROPAGATION OF PERTURBATION ENERGY FLUXES IN THE SUBSOLAR MAGNETOSHEATH: AMPTE IRM OBSERVATIONS

N. Lin[1], M. J. Engebretson[1], W. Baumjohann[2], and H. Luehr[3]

Abstract We have studied the propagation properties of perturbation energy fluxes of subsolar magnetosheath fluctuations. The Poynting flux, kinetic energy flux, and enthalpy flux are calculated using magnetic field and plasma measurements from the AMPTE IRM satellite during five intervals in 1984. The results are then compared with a disturbance indicator R of the magnetic field in the same magnetosheath region. It is shown that during disturbed periods with large transverse variations (low R level), the perturbation Poynting flux and the kinetic energy flux increase, and a significant portion of the fluxes consistently propagates toward the magnetopause. The Poynting flux of those fluctuations which consist of mainly compressional perturbations does not appear to propagate in any certain direction. The enthalpy flux of the perturbations does not propagate in any certain direction in any of the cases. The kinetic energy flux appears to be more important in exciting harmonic ULF waves in the dayside magnetosphere. What portion of this energy flux is transferred into the magnetosphere needs further investigation.

Introduction

Previous studies have shown that a certain class of disturbances of the magnetic field and plasma in the subsolar magnetosheath is correlated wih azimuthally polarized harmonic oscillations of the magnetic field in the dayside outer magnetosphere. Recent observations [Engebretson et al., 1991, and Lin et al., 1991, denoted here as Paper 1 and Paper 2] indicate that dayside magnetospheric Pc 3-4 pulsation activity and low IMF cone angles are correlated with increased turbulence in the subsolar magnetosheath plasma and magnetic field. During times Pc 3-4 pulsations were observed, magnetosheath magnetic fields exhibited large irregular variations in both magnitude and direction, and magnetosheath plasma showed evidence of significant energization and also of irregular variations in density and velocity. Purely compressional waves were at times observed, but were associated with neither upstream waves nor magnetospheric pulsations. In Paper 2 Lin et al. defined a disturbance parameter, R, to indicate the extent of disorder of the magnetic field of the subsolar magnetosheath. The parameter is expressed as the normalized resultant of magnetic vectors:

$$R = (1/n) \left| \sum_{i=1}^{n} \mathbf{B}_i / |\mathbf{B}_i| \right| \qquad (0 \leq R \leq 1)$$

where n is the number of measurements of vector **B** in a time interval. R decreases to a low level (less than 0.8) when fluctuations that consist of strong transverse components and are associated with magnetospheric wave activity intensify, while it remains near 1 when the fluctuations are small or basically compressional.

There have been only few studies of the propagation of waves in the magnetosheath. In a recent case study, Gleaves and Southwood [1990] have observed a transverse magnetic disturbance in the magnetosheath and determined the propagation direction of the wave front as along the inward shock normal and across the ambient magnetic field. However, the waves they observed apparently originated in the quasi-perpendicular bow shock region and appeared to be unrelated to upstream waves. In an attempt to understand the role magnetosheath fluctuations play in transferring the energy into the magnetosphere, we investigate in this study the propagation of energy fluxes of magnetosheath fluctuations, and compare properties of the fluxes with the disturbance parameter R under various magnetosheath conditions. The five periods on days 261, 252, 272, 283, and 254 of 1984 that were used in Papers 1 and 2 were also used for this study. Figure 1 shows the trajectories of AMPTE IRM during the five periods. The arrows indicate the direction of the spacecraft motion. Each period covers the entire subsolar magnetosheath crossing, except for the very ends, where it encounters the bow shock or the magnetopause.

The energy fluxes we examined include the Poynting flux, the kinetic energy flux and the enthalpy flux [cf. Birn et al., 1985], calculated using magnetic field and plasma data. The total Poynting flux is $\mathbf{S} = (1/\mu_o)[\mathbf{B} \times (\mathbf{V} \times \mathbf{B})]$ where $\mu_o = 4\pi 10^{-7}$ sec^2/m^2, and **B** and **V** are measured magnetic field vectors and plasma velocity vectors, respectively. We then define $\mathbf{B} = \mathbf{B}_o +$

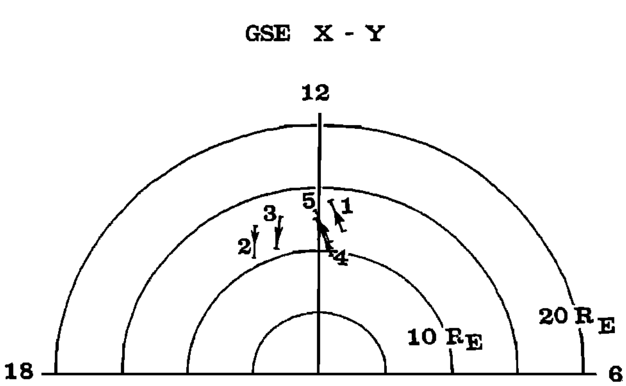

Fig. 1. Trajectories of the AMPTE IRM spacecraft as projected to the equatorial plane of the GSE coordinate system during the five events. Each location is labeled by the number of the corresponding event: (1) September 17, 1984 (day 261), 2200 - 2400 UT. (2) September 28, 1984 (day 272), 1045 - 1215 UT. (3) October 9, 1984 (day 283), 1200 - 1400 UT. (4) September 8, 1984 (day 252), 1500 - 1700 UT. (5) September 10, 1984 (day 254), 1200 - 1400 UT.

[1]Dept. of Physics, Augsburg College, Minneapolis, MN
[2]Max-Planck-Institut fur Extraterrestrische Physik, Garching, Germany
[3]Institut fur Geophysik und Meteorologie der Technischen Universitat Braunschweig, Braunschweig, Germany

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b and $\mathbf{V} = \mathbf{V}_o + \mathbf{v}$, where $\mathbf{B}_o$ and $\mathbf{V}_o$ are the average magnetic field and velocity vectors, while **b** and **v** are the perturbation magnetic field and perturbation velocity, respectively. $\mathbf{B}_o$ and $\mathbf{V}_o$ are calculated as the 55-point running average of **B** and **V**. The instrumentation we used in this study has been described in Paper 1. The data we use have a resolution of 4.4 seconds with every fifth point missing, thus 55 data points cover about 297 seconds which is a much larger time scale than the scale of ULF variations (10 - 50 sec) being studied. We define the background Poynting flux as $\mathbf{S}_o = (1/\mu_o)[\mathbf{B}_o \times (\mathbf{V}_o \times \mathbf{B}_o)]$ and the perturbation Poynting flux is then $\mathbf{S}_1 = \mathbf{S} - \mathbf{S}_o$. The kinetic energy flux is $\mathbf{K} = (1/2)M_p N_p V^2 \mathbf{V}$, where M_p and N_p are the mass and density of protons, respectively. We take the average kinetic energy flux as $\mathbf{K}_o = (1/2)M_{po} N_{po} V_o{}^2 \mathbf{V}_o$, where M_{po} and N_{po} are the running average of M_p and N_p over 55 data points. The perturbation kinetic energy flux is thus $\mathbf{K}_1 = \mathbf{K} - \mathbf{K}_o$. Similarly, we calculate the perturbation enthalpy flux as $\mathbf{E}_1 = \mathbf{E} - \mathbf{E}_o$, where the total enthalpy flux is $\mathbf{E} = (5/2)\ p\ \mathbf{V}$, and the thermal pressure $p = N_p k T_p$, where k is Boltzmann's constant, and T_p is the proton temperature. $\mathbf{E}_o$ is the average enthalpy flux which equals (5/2) $N_{po} k T_{po}$. The unit used for energy fluxes in this report is 10^{-5} Watts/m ^{2}. All quantities of energy fluxes presented here have been averaged over 5 data points (about 22 s), approximately the time scale of the period of the fluctuations.

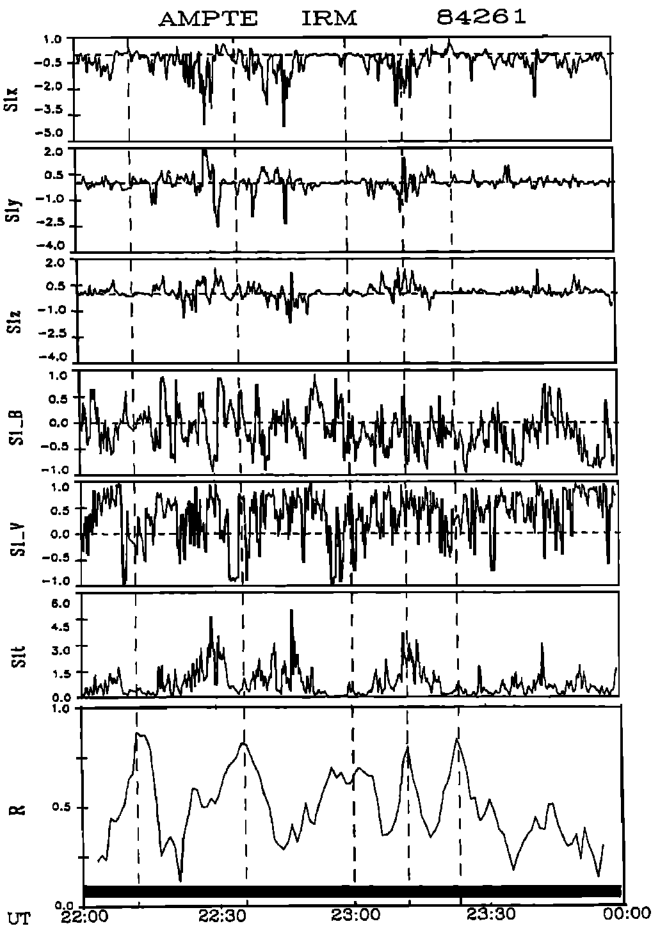

Fig. 2a. Perturbation energy fluxes for Event 1, 2200 to 2400 UT September 17, 1984 (day 261). Shown in this figure are components and magnitude of the perturbation Poynting flux and R parameter, as defined in the text.

Data Presentation

In this section we present calculated energy fluxes of two events as examples.

Event 1: 2200 - 2400 UT September 17, 1984 (Day 84261)

This magnetosheath crossing occurred on a magnetically quiet day (K_p = 1- for the interval), but the IRM magnetosheath data show turbulent magnetic disturbances throughout the interval. The spacecraft was travelling outbound at about 12 R_E from the Earth. During this period, the IMF cone angle (not shown) was mostly <40°.

Figure 2a displays, in the first three panels, the GSE x, y and z components of the S_1 vector, S1x, S1y, and S1z. In the fourth and fifth panels, we have plotted the fractions of the magnitude of S_1, S1B and S1V, which are in the directions of $\mathbf{B}_o$ and $\mathbf{V}_o$, respectively, with positive values for the fractions in the direction parallel to $\mathbf{B}_o$ or $\mathbf{V}_o$, and negative values antiparallel. The fractions were calculated as the cosine of the angle between S_1 and $\mathbf{B}_o$ or $\mathbf{V}_o$. The sixth panel shows the magnitude of S_1, S1t. In the last panel, we show the magnetic disturbance indicator R. The period when harmonic waves were observed by AMPTE CCE in the dayside outer magnetosphere is marked with a bar in the last panel.

Figure 2a shows that when R goes low, indicating intensified disturbances in this magnetosheath region, the magnitude of the perturbation Poynting vector S1t increases, and in the x direction, the S_1 vector is mainly negative, i.e., towards the magnetosphere. In the y and z directions, S_1 has no consistent direction. Panels 4 and 5 show that when R is low a large portion of S_1 propagates in the $\mathbf{V}_o$ direction but with no consistent direction

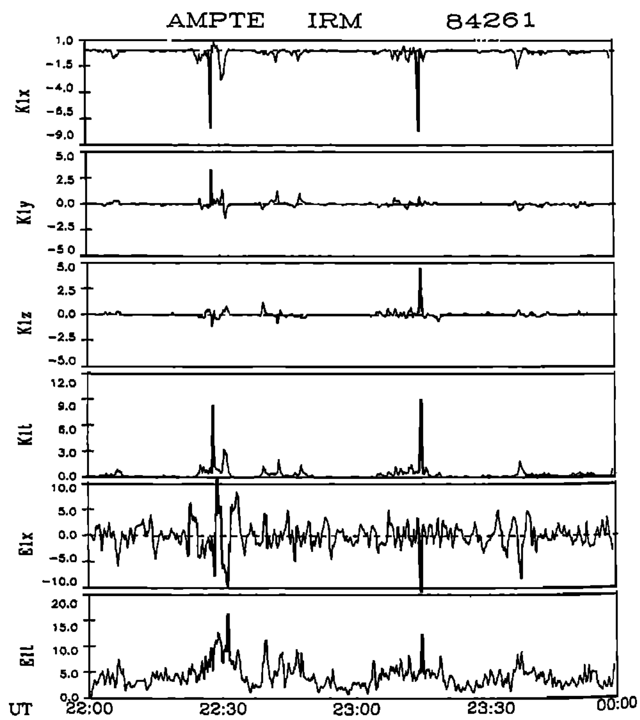

Fig. 2b. Perturbation energy fluxes for Event 1, 2200 to 2400 UT September 17, 1984 (day 261). Shown in this figure are components and magnitudes of the perturbation kinetic energy flux and enthalpy flux, as defined in the text.

with respect to $\mathbf{B}_o$. During some brief intervals when R was relatively high, implying less disturbed states, (e.g. near 2210, 2235, 2300, and 2320 UT, which are marked by vertical dashed lines), S1t decreased remarkably and S1V also decreased or fluctuated between positive and negative values. The short period of high R near 2310 UT is a clear exception, however. Note that $\mathbf{S}_1$ is not aligned with either $\mathbf{B}_o$ or $\mathbf{V}_o$, since a cosine of 0.7 in S1V still implies an angle of about 45° between $\mathbf{S}_1$ and $\mathbf{V}_o$.

The first four panels of Figure 2b show the three components of the perturbation kinetic energy flux, K1x, K1y and K1z, and its magnitude K1t. The last two panels of the figure display the x component of the perturbation enthalpy flux, E1x, and its magnitude E1t. Figure 2b also shows that $\mathbf{K}_1$ increases when perturbations intensify, and has a consistent -x component. The perturbation enthalpy flux $\mathbf{E}_1$ is in general larger in magnitude than $\mathbf{S}_1$ or $\mathbf{K}_1$, but E1x, as well as E1y and E1z (not shown), fluctuates around zero showing no consistent propagation direction. The above characteristics of the perturbation enthalpy flux are consistent in all five cases we studied.

Event 2: 1045 - 1215 UT September 28, 1984 (Day 84272)

This crossing occurred during a moderate magnetically disturbed period with K_p ~ 2 to 3. AMPTE IRM was inbound, ~ 12 R_E from the Earth and near 1400 local time. In Figure 3, we display, from the top to the bottom panels, S1x, S1t, S1B, S1V, K1x, K1t, and R, which are all defined as in Figure 2. The disturbance parameter R shows that the subsolar magnetosheath region was relatively turbulent before 1135 UT and after 1205 UT (marked by vertical dashed lines). The IMF cone angle measured from ISEE 1 (not shown) was mostly >135° before 1130 UT and mostly <135° between 1130 and 1205 UT. Harmonic oscillations were observed by CCE before ~ 1145 UT.

Figure 3 shows that S1t remained at about the same level throughout the entire interval. The magnetic field data (see Paper1) showed that there were substantial compressional fluctuations during the high R period between 1135 and 1205 UT. This compressional wave had slow mode characteristics: the ion density oscillated in antiphase with the magnetic field (not shown). We see that during the disturbed period before 1135 and after 1205 UT, S1x was essentially negative, implying a propagation towards the magnetosphere, and the S1V panel shows that a significant portion of $\mathbf{S}_1$ propagated in the plasma flow direction. During the high R period, a greater fraction of $\mathbf{S}_1$ went in the +x direction although negative S1x still dominated, and S1V fluctuated around zero. The magnitude of the perturbation kinetic energy flux, K1t, was higher before 1135 UT than after, and the K1x panel indicates that $\mathbf{K}_1$ propagated mainly towards the magnetosphere.

Summary and Discussion

In the five events we studied, we found that the following properties of perturbation energy fluxes are in common:

(1) The perturbation Poynting flux increases when transverse and compressional fluctuations intensify. The Poynting flux of those fluctuations which consist of mainly compressional perturbations does not appear to propagate in a certain direction, while the Poynting flux of those fluctuations which contain strong transverse perturbations tends to have a significant -x component, i.e. in the direction towards the magnetosphere. The transverse fluctuations are what can be measured by the R parameter and correlate with harmonic Pc 3-4 oscillations occurring in the dayside outer magnetosphere.

(2) The transverse perturbations do not seem to propagate along magnetic field lines. Instead, a large portion of their Poynting flux propagates in the direction of the average plasma velocity.

(3) The kinetic energy flux of fluctuations, $\mathbf{K}_1$, increases only when R decreases, i.e., when the transverse fluctuations are enhanced. During disturbed periods, the magnitude of the perturbation kinetic energy flux $\mathbf{K}_1$ is comparable to that of the perturbation Poynting flux $\mathbf{S}_1$, and $\mathbf{K}_1$ always has a significant component in the -x direction, i.e., it propagates towards the magnetopause.

(4) The enthalpy flux of the perturbation is larger in magnitude than the above two energy fluxes, but it does not have a preferred direction.

As a brief summary, we list some results from the five magnetosheath crossings in Table 1. Shown in the table are the average of six quantities: S1t, S1x, St, K1t, K1x, and Kt. The averages were taken over corresponding intervals listed in the first column. We note that, during the interval on day 252 when the subsolar magnetosheath appeared as a quiet state with high R values [see Paper 2], S1t was relatively high, but the portion that propagated towards the magnetosphere was very low.

Both transverse and compressional fluctuations in the magnetosheath have been previously observed. Luhmann et al.

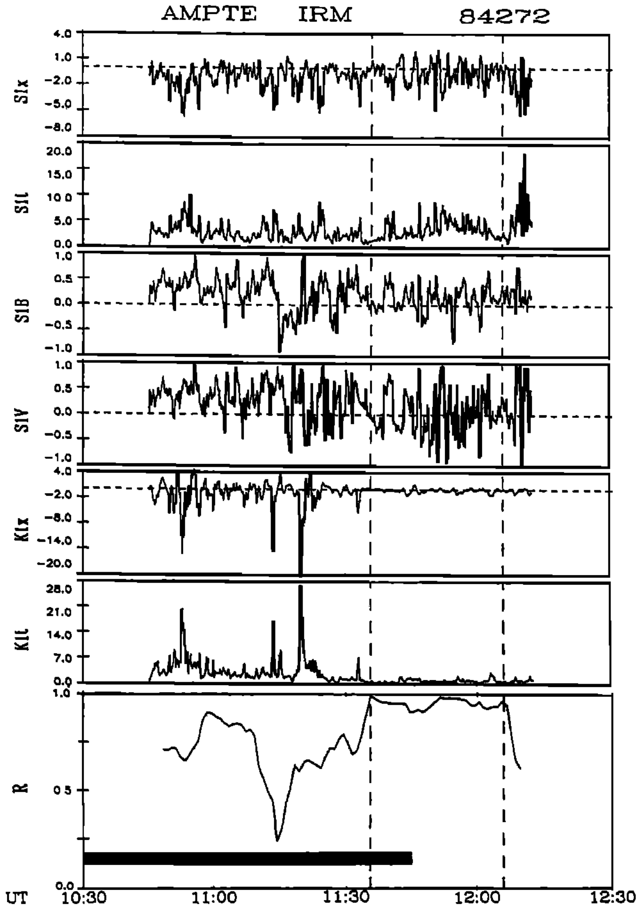

Fig. 3. Perturbation energy fluxes for Event 2, 1045 - 1215 UT September 28, 1984 (day 272). Note that the scales for S1x, S1t, K1x and K1t are different from corresponding panels in Figure 2.

[1986] related both types of fluctuations in the subsolar magnetosheath to the subsolar quasiparallel shock. In our earlier study of those five events [Papers 1 and 2] we showed that it is the fluctuations of the magnetosheath magnetic field, which were characterized by rapid direction changes (and thus contained strong transverse components) and can be measured by the R parameter, as well as strong plasma heating and greatly increased values of thermal and dynamic plasma beta, that correlated to the occurrence of the harmonic Pc 3, 4 waves in the magnetosphere. It is noted [Paper 1] that the transverse variations in the magnetic field of the magnetosheath were not sinusoidal, while the compressional ones were more sinusoidal. Our results seem to support the above correlation: during disturbed states (low R periods), a significant part of the fluctuation energy of the magnetosheath consistently propagates towards the magnetopause in the form of perturbation Poynting flux and kinetic energy flux. Either or both of these fluxes might play a role in transferring perturbation energy from the quasi-parallel shock regions into the magnetosphere, and provide energy for the harmonic oscillations. We note that S_1 does not appear to propagate along the ambient magnetic field, and it is not entirely convected with the plasma flow either, although it may have a significant component in the V_0 direction. Apparently, the wave energy during disturbed (low R) periods propagates across the ambient field lines, with part of it consistently flowing toward the magnetosphere.

Table 1 shows that <K1x> changes much more significantly from a disturbed state to a quiet one than <S1x> does. <K1x> decreases to a much lower level during quiet periods than during disturbed periods. This may imply that the kinetic energy flux is more important than the Poynting flux for waves in the magnetosheath in transferring the wave energy toward the magnetosphere. What portion of the energy fluxes (S_1 and K_1) is eventually transferred into the magnetosphere is still unknown. From the five events we studied, it seems that the transfer rate differs from one event to another. It is not determined by the absolute amount of the energy flux which propagates in the -x direction. For example, Table 1 shows that during the disturbed period on day 261, <S1x> was only -0.4 units and <K1x> was -0.2 unit, but weak harmonic waves were observed in the magnetosphere. In contrast, during the quiet periods on days 283 and 272, <S1x> was -0.6 units (<K1x> decreased to -0.1), but no harmonic waves were observed in the magnetosphere. How these energy fluxes are transmitted through the magnetopause still needs further investigation.

Table 1. Summary of calculated energy fluxes for the five events

Interval	<S1t>	<S1x>	<St>	<K1t>	<K1x>	<Kt>
(1) 84261 2200-2400 (disturbed)	0.8	-0.4	0.9	0.4	-0.2	0.5
(2) 84272 a.1045-1135 (disturbed)	3.0	-1.1	3.5	3.9	-1.0	7.8
b.1135-1205 (quiet)	3.6	-0.6	6.3	0.9	-0.1	3.6
(3) 84283 a.1210-1240 (disturbed)	3.9	-1.8	4.1	2.8	-1.1	3.6
b.1245-1400 (quiet)	4.9	-0.6	9.8	0.8	-0.1	1.6
(4) 84252 a.Before 1510 and After 1610 (slightly disturbed)	8.0	-0.8	15.4	0.3	0.0	0.7
b.1510-1610 (quiet)	6.8	-0.3	14.0	0.2	0.0	0.5
(5) 84254 a.1235 - 1315 (slightly disturbed)	3.0	-0.3	4.3	0.6	-0.1	1.1
b. after 1315 (disturbed)	5.7	-2.3	7.5	4.2	-1.9	5.5

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References

Birn, J., E. W. Hones, Jr., S.J. Bame, and C. T. Russell, Analysis of 16 plasma vortex events in the geomagnetic tail, *J. Geophys. Res.*, 90, 7449, 1985.

Engebretson, M. J., N. Lin, W. Baumjohann, H. Luehr, B. J. Anderson, L. J. Zanetti, T. A. Potemra, R. L. McPherron, and M. G. Kivelson, A comparison of ULF fluctuations in the solar wind, magnetosheath, and dayside magnetosphere, 1. Magnetosheath morphology, *J. Geophys. Res.*, 96, 3441, 1991.

Gleaves, D. G., and D. J. Southwood, Phase delays in transverse disturbances in the Earth's magnetosheath, *Geophys. Res. Lett.*, 17, 2249, 1990.

Lin, N., M. J. Engebretson, R. L. McPherron, M. G. Kivelson, W. Baumjohann, H. Luehr, T. A. Potemra, B. J. Anderson, and L. J. Zanetti, A comparison of ULF fluctuations in the solar wind, magnetosheath, and dayside magnetosphere, 2. Field and plasma conditions in the magnetosheath, *J. Geophys. Res.*, 96, 3455, 1991.

Luhmann, J. G., C. T. Russell, and R. C. Elphic, Spatial distributions of magnetic field fluctuations in the dayside magnetosheath, *J. Geophys. Res.*, 91, 1711, 1986.

W. Baumjohann, Max-Planck-Institut fur Extraterrestrische Physik, Garching, Germany.

N. Lin and M. J. Engebretson, Dept. of Physics, Augsburg College, Minneapolis, MN 55454.

H. Luehr, Institut fur Geophysik und Meteorologie der Technischen Universitat Braunschweig, Braunschweig, Germany.

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