TRANSFER OF PULSATION-RELATED WAVE ACTIVITY ACROSS THE MAGNETOPAUSE:
OBSERVATIONS OF CORRESPONDING SPECTRA BY ISEE-1 AND ISEE-2

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Abstract. Comparison of power spectra of magnetic field data from ISEE-1 and -2 recorded simultaneously on both sides of the magnetopause showed that power level inside the magnetosphere varied with power level outside in the magnetosheath and suggested that the same frequencies were enhanced on the two sides of the boundary. Power levels were two to three orders of magnitude lower inside than outside the magnetosphere, indicating that wave energy was transmitted inside from the sheath, through a locally stable magnetopause.

Introduction

A persistent and significant, although weak and disordered, correlation between solar wind properties and daytime geomagnetic pulsation activity in the Pc 3,4,5 range, periods $T=10$ to 500sec, has been established by many reports [Bol'shakova and Troitskaya, 1968; Gul'elmi, 1974; Webb and Orr, 1976; Saito et al., 1979; Greenstadt et al., 1979; Wolfe et al., 1980]. A more comprehensive summary and reference list can be found in a paper by Greenstadt et al. [1980]. Waves constituting the pulsations must, in the most general terms, be produced inside the magnetosphere, emanate from the boundary surface separating the magnetosheath and the magnetosphere (i.e. from the magnetopause), or enter the magnetosphere from the magnetosheath. None of these possible sources excludes either of the others, but certainly if waves enter the magnetosphere from outside, they must cross the boundary somewhere at some time, and it should be possible to establish by observation a physical similarity between waves detected simultaneously on both sides of the magnetopause. This is the approach advocated by Wolfe and Kaufmann [1975], and which we pursue in the present study; the preliminary results reported here support the transfer of wave energy inward from the magnetosheath to the magnetosphere, under the most adverse conditions from a theoretical viewpoint [Verzariu, 1971; Wolfe and Kaufmann, 1975].

We define as a "straddle" a situation in which one spacecraft is on one side of the magnetopause and a second is on the opposite side. The ISEE-1 and -2 satellites provided many such straddle crossings, but we have concentrated on the magnetometer data of 1978, when the spacecraft were separated by hundreds to thousands of km for several months, giving straddles long enough for unequivocal analyses of waves with periods up to several minutes. Our approach is to compute concurrent power spectra on both sides of clearly defined magnetopause crossings and to seek similarities or differences in the spectra from the two spacecraft. We require reasonably

continuous data from both satellites over minimal intervals of 15 minutes and preferably much longer. We found four potentially suitable straddles of which we have developed two for this preliminary report, supplemented by two single-spacecraft crossings, as explained later. We present only spectra of the total field magnitude at this time, derived from vector samples every two seconds.

Data

The two cases we describe occurred on 8 October and 27 November 1978. The 8 October crossing occurred in early afternoon, the 27 November crossing in late morning. The daytime surface field for our cases was measured by the AFGL ground stations in a sector spanning the United States near 55 degrees magnetic latitude. Ground station data processed for this report were recorded by the Newport station at the western edge of the sector, which fell before and after noon during the two intervals of interest, so that the morning-afternoon local times on the ground were reversed from those of our crossings at the magnetopause. We used ground station data as a rough guide to the presence of traditional pulsations on the ground, since it is waves related to the origin of such pulsations that we wish to be studying.

Power spectra presented in this study were calculated with the fast Fourier transform. Figure 1 places one spectrum, dotted curve, on the same scales used by Fairfield [1976] to display the characteristics of magnetosheath magnetic noise from several spacecraft. The dotted curve is a power spectrum for the total ambient field recorded by ISEE-1 immediately outside the magnetopause on 8 October. All spectra are for the total field magnitude; details of the earlier spectra can be found in Fairfield's review [op.cit.].

The figure illustrates four principal points: magnetosheath spectra typically show either an enhancement or a slope change, or both, at or below the local proton gyrofrequency (highlighted by the dashed lines); second, magnetosheath spectra are highly variable, both in absolute power level and in the frequencies that might be enhanced in any particular sample; third, spectra taken from ISEE data years later are reasonably representative of the same wave behavior that prevailed during the earlier measurements. Fourth, and most importantly for this report, spectra obtained from ISEE close to the magnetopause do not appear to define a special region in any way unrepresentative of the magnetosheath at other locations.

Figure 2a is an example of our first straddle case. The upper panels of the figure display plots of field magnitude from ISEE-1 and ISEE-2, for the magnetopause crossing of 8 October 1978. ISEE-2, lower field plot, entered the magnetosphere first at 1805:50 and finally at 1813; ISEE-1, top, encountered the magnetosphere later, initially at 1831 and entered finally at 1835:40. Thus, there were 18 minutes during which data were acquired simultaneously

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Fig. 1. An ISEE-1 magnetosheath spectrum obtained near the magnetopause (dots), superposed on a selection of spectra from earlier spacecraft in the magnetosheath.

from one satellite outside and one inside the magnetopause.

Spectrum A shows the wave power in the total field in the magnetosheath just outside the magnetopause, at ISEE-1. The next spectrum below, B, shows the wave power in the magnetosphere just inside the magnetopause, at ISEE-2, for the same time interval as that of the first spectrum. The power was appreciably lower and the decrease in power with frequency clearly much steeper inside than outside the magnetopause, beginning with about one third the outside power at the lowest frequencies. At 0.1 Hz, there were three orders of magnitude difference between the two spectra.

Spectrum G, at bottom, represents the power on the ground at the AFGL station at Newport, Washington, for the same intervals as in the depicted satellite samples. The ground station was a few hours west of the satellites, about 1100 local time. The shaded vertical strips in the spectral panels draw attention to the enhancements in power at the satellites and on the ground that appear to bind wave activity together in the inner magnetosheath, the outermost magnetosphere, and at the earth's surface. All the spectra show some concentration of power between 0.02 and 0.07 Hz in the form of a plateau or peaks in the respective curves.

Figure 2a shows a progressive decline in power from the magnetosheath to the earth's surface. Each spectral curve is contained in, i.e. accounts for a fraction of the power of, the next spectrum above it. The magnetospheric spectra are well below that of the magnetosheath and are closer to one another than to the latter, the discrepancy being greatest at the highest frequencies.

Figure 2b superposes spectra from a second straddle case on 27 November 1978, when ISEE-1 was just outside the magnetopause. ISEE-2 was deeper inside the magnetosphere, having entered at 2000 UT, than it had been on 8 Oct., and the Newport station was below and east of the satellite meridian (in the early afternoon sector). In this instance, the power in the sheath (A) displayed enhancement and a plateau between 0.011 and 0.05 Hz, as did also the power in the magnetosphere (B), while the corresponding power on the ground (G) was relatively featureless, but essentially at the same level as at ISEE-2 for the higher frequencies. Local effects may have boosted the power on the ground at the lowest frequencies. Whether the apparent lack of any frequency peak on the ground at this time was because of a delayed effect not yet visible, an unfavorable position in the afternoon sector, or

a poor choice of representation of the surface record is still to be determined. The small graph at the bottom shows the power distribution in B_y (D-component) at Newport for the local noon and afternoon interval including the 22-minute segment of the upper graph; clearly, there was some activity in the surface field within the longer interval and within the enhanced portion of the spectrum at the satellites. The attenuation of wave power across the magnetopause is obvious here, as in the previous case, but we also see that the frequency range of enhancement was shifted to somewhat lower frequencies, in all locations, than in the case of 8 October, as indicated by the shading in Figure 2.

The magnetosheath spectra of 8 Oct. and 27 Nov. are superposed in Fig. 3, showing that the power of the 27 Nov. spectrum peaked at lower frequency and dropped more rapidly than the power on 8 Oct., almost as if translated to the left for frequencies above 0.02 Hz. This difference corresponds to the slightly different regions of the frequency scale that seemed to show enhanced power in the magnetosphere, as shaded in Figure 2. Unfortunately, the absolute power levels in the magnetosheath in the two cases examined above did not differ appreciably from each other, considering the wide range of power exhibited in the curves of Figure 1. In order to study whether power inside the magnetosphere is related generally to power in the magnetosheath, it was necessary to examine nonstraddle cases. On the premise that the sheath spectrum remained substantially unchanged from one interval to the next over an hour's time, we selected cases with significantly different power levels and compared spectra before and after magnetopause crossing, rather than simultaneous spectra on opposite sides of the boundary. Corresponding magnetosheath and magnetosphere spectra are superposed in Figure 4 for three days, 8 October, and 10 and 17 September 1978. The 8 October curves are already familiar. The new ones show that progressively lower power in the sheath corresponded to progressively lower power in the magnetosphere, suggesting, with these few cases and the necessary assumption of stationarity on the 10th and 17th, that the powers inside and outside the magnetopause were directly related.

Fig. 2. Magnetic field magnitude records and superposed spectra for two cases of ISEE-1, ISEE-2 straddles of the magnetopause: (a) 8 Oct., (b) 27 Nov., 1978; A, B, and G signify spectra for the indicated intervals at ISEE-1, ISEE-2, and the AFGL Newport ground station. The insert at bottom right covers a longer interval at Newport, as noted; LT=UT-8.

Summary

The data presented above may be summarized as follows, with the understanding that we refer essentially to the frequency range $0.01 < f < 0.1$ Hz (periods $10 < T < 100$ sec., i.e. Pc 3 and part of the Pc 4 band):

The power within the magnetosheath was 10 to 1000 times the power in the magnetosphere;
The power within the magnetosphere varied less than a factor of 10 from the magnetopause to the surface;
The power level inside the magnetosphere correlated overall with power level outside the magnetopause;
The frequency of power enhancement in the magnetosphere appeared to shift with the frequency of power enhancement in the magnetosheath.
The power outside the magnetopause appeared to be representative of power in the magnetosheath generally.

Discussion

Similarity of spectra across the magnetopause could be caused by a commonality of waves travelling in any direction. The ratios of power in the magnetosphere to power in the magnetosheath in our period range of principal interest ran from about 0.001 to 0.08. Such low ratios are consistent with power transferred inward across stable magnetopause boundaries, i.e. tangential discontinuities, for which similar ratios were predicted by Verzariu [1973] and observed in single-satellite crossings by Wolfe and Kauffman [1975]. Of course, a criterion by which we selected cases was the appearance of a clear, stable magnetopause allowing us easily to determine that one spacecraft was inside, the other outside the boundary. Thus, low power ratios eliminate both directly and indirectly, wave propagation outward along field lines locally interconnecting the solar wind to the magnetosphere. They also make surface waves unlikely; the newest calculations of surface wave effects [Pu and Kivelson, 1983] require that the magnetic wave power inside the boundary exceed that outside, opposite our results. Naturally, there could have been contributions to the magnetosheath waves from surface or internal sources, and almost certainly from wave reflection [Fejer, 1963], but they are unlikely to have accounted for the power or shape of the sheath spectra.

The asserted commonality of frequency enhancement across the boundary, as illustrated here in Figure 2, is subtle at best. This is hardly surprising, since we are dealing with a global phenomenon notoriously elusive to sharply defined correlations, which we chance to sample as a few straddles and a few crossings of diverse power, at a few points in space. We chose the two examples here as

Fig. 3. Superposed magnetosheath spectra from 8 Oct. and 27 Nov.

Fig. 4. Superposed power spectra for three different power levels in the magnetosheath and magnetosphere on three different days.

the purest straddle cases. Other spectra, with more persuasive enhancement profiles, were obtained in data contexts requiring more exposition than could be included in this letter and will be the subject of a separate report. The similarities of enhancement are important because, even though power is transmitted more readily across an open magnetopause, i.e. across interconnected field lines, or rotational discontinuities [Lee, 1982], there is no evidence that the southward interplanetary field ($B_z < 0$) associated with such a condition is correlated with Pc 3,4 occurrence [Wolfe, 1980]. Thus, transmission at low power ratios, under adverse conditions, may be the key to solar wind control of pulsation activity.

Experience does not encourage heavy confidence in the premise of spectral constancy on which Wolfe and Kaufmann [1975] depended, and on which we have leaned for Figure 4, but our straddle examples add a little more weight to the body of evidence favoring an external source of Pc 3,4. We conclude therefore that our preliminary results are consistent with external wave origin, specifically with the transfer of a small fraction of magnetosheath wave power, possibly derived from quasi-parallel shock structure [Greenstadt, 1972; Kovner et al., 1976], across a stable magnetopause, into the magnetosphere to appear as waves in the Pc 3-4 range. Component-by-component details of the transfer process, the global picture describing where the most effective transfer takes place, and the pathways whereby broadband energy in the magnetosheath is recorded as monochromatic pulsations in the magnetosphere remain to be determined.

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References

- Bol'shakova, O. V., and V. A. Troitskaya, Relation of the interplanetary magnetic field direction to the system of stable oscillations, *Dokl. Akad. Nauk SSSR*, 180, 4, 1968.

- Fairfield, D. H., Magnetic fields of the magnetosheath, *Rev. Geophys. Space Phys.*, **14**, 117, 1976.
- Fejer, J. A., Hydromagnetic reflection and refraction at a fluid velocity discontinuity, *Phys. Fluids*, **6**, 508, 1963.
- Greenstadt, E. W., Field-determined oscillations in the magnetosheath as possible source of medium-period, daytime micropulsations, in *Proceedings of Conference on Solar Terrestrial Relations*, 515, Univ. of Calgary, April 1972.
- Greenstadt, E. W., H. J. Singer, C. T. Russell, and J. V. Olson, IMF orientation, solar wind velocity, and Pc3-4 signals: a joint distribution, *J. Geophys. Res.*, **84**, 527, 1979.
- Greenstadt, E. W., R. L. McPherron, and K. Takahashi, Solar wind control of daytime, midperiod geomagnetic pulsations, *J. Geomag. Geoelectr.*, **32**, Suppl. II, SII 89, 1980.
- Gul'elmi, A. V., Diagnostics of the magnetosphere and interplanetary medium by means of pulsations, *Space Sci. Rev.*, **16**, 331, 1974.
- Kovner, M. S., V. V. Lebedev, T. A. Plysova-Bakunina, and V. A. Troitskaya, On the generation of low-frequency waves in the solar wind in the front of the bow shock, *Planet. Space Sci.*, **24**, 261, 1976.
- Lee, L. C., Transmission of Alfvén waves through the rotational discontinuity at magnetopause, *Planet. Space Sci.*, **30**, 1127, 1982.
- Pu, Z.-y., and M. G. Kivelson, Kelvin-Helmholtz instability at the magnetopause: Energy flux into the magnetosphere, *J. Geophys. Res.*, **88**, 853, 1983.
- Saito, T., I. Yumoto, K. Takahashi, T. Tamura, and T. Sakurai, Solar wind control of Pc 3, magnetospheric study 1979, in *Proceedings of International Workshop on Selected Topics of Magnetospheric Physics*, 155, Japanese IMS Committee, Tokyo, 1979.
- Verzariu, P., Reflection and refraction of hydromagnetic waves at the magnetopause, *Planet. Space Sci.*, **21**, 2213, 1973.
- Webb, D., and D. Orr, Geomagnetic pulsations (5-50 mHz) and the interplanetary magnetic field, *J. Geophys. Res.*, **81**, 5941, 1976.
- Wolfe, A., Dependence of mid-latitude hydromagnetic energy spectra on solar wind speed and interplanetary field direction, *J. Geophys. Res.*, **85**, 5977, 1980.
- Wolfe, A. and Kaufmann, R. L., MHD wave transmission and production near the magnetopause, *J. Geophys. Res.*, **80**, 1764, 1975.
- Wolfe, A., L. J. Lanzerotti, and C. G. MacLennan, Dependence of hydromagnetic energy spectra on solar wind velocity and interplanetary magnetic field direction, *J. Geophys. Res.*, **85**, 114, 1980.

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