

THE QUASIPERPENDICULAR ENVIRONMENT OF LARGE MAGNETIC PULSES
IN EARTH'S QUASIPARALLEL FORESHOCK: ISEE 1 & 2 OBSERVATIONS

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Abstract. ULF waves in Earth's foreshock cause the instantaneous angle ϑ_{Bn} between the upstream magnetic field and the shock normal to deviate from its average value. Close to the quasiparallel (Q_{\parallel}) shock the transverse components of the waves become so large that the orientation of the field to the normal becomes quasiperpendicular (Q_{\perp}) during applicable phases of each wave cycle. Large upstream pulses of B were observed completely enclosed in excursions of ϑ_{Bn} into the Q_{\perp} range. A recent numerical simulation included ϑ_{Bn} among the parameters examined in Q_{\parallel} runs, and described a similar coincidence as intrinsic to a stage in development of the reformation process of such shocks. Thus, the natural environment of the Q_{\parallel} section of Earth's bow shock seems to include an identifiable class of enlarged magnetic pulses for which local Q_{\perp} geometry is a necessary association.

Introduction

Waves associated with locally quasiparallel (Q_{\parallel}) structure in Earth's foreshock and bow shock cause the angle ϑ_{Bn} between the upstream field \mathbf{B} and the nominal shock normal \mathbf{n} to vary between wide extremes. Greenstadt and Mellott [1985] noted that the defining boundary between solar wind and magnetosheath seemed to be consistently characterized by high, average ϑ_{Bn} , i.e., quasiperpendicular (Q_{\perp}) geometry, just outside and downstream from the boundary. They also noted that some large amplitude pulses in field strength typical of Q_{\parallel} phenomenology upstream from the shock seemed to be accompanied, if not actually enclosed, by excursions of ϑ_{Bn} into the Q_{\perp} range ($45^{\circ} < \vartheta_{Bn} < 90^{\circ}$). However, they examined only a few cases and only with 12-s averaged data from the ISEE 1 and 2 magnetometers in 4-s/average plots. In some cases the rises in B ($\equiv |\mathbf{B}|$) and ϑ_{Bn} were virtually simultaneous, so details were lost in the early survey.

Since the earlier report, some simulators have included local, or instantaneous, ϑ_{Bn} among the variable parameters they examined [Thomas et al., 1990; Winske et al., 1990]. Most notably, a recent one-dimensional simulation found a definite connection between enlarged ϑ_{Bn} and

the point in the history of a convecting upstream wave where it encounters reflected beams [Scholer and Burgess, 1992]. This report demonstrates that a locally Q_{\perp} environment surrounded a set of independently selected upstream pulses when these are examined at the highest resolution available to the ISEE 1 and 2 instruments. Our results are compatible with recent simulations and a scenario for pulse development at the Q_{\parallel} bow shock.

Data

The examples of this report are represented by magnetic field measurements sampled 4 or 16 times per second, depending on the rate in effect at the time of observation, using the UCLA fluxgate magnetometers of ISEE 1 and 2 [Russell, 1978]. Shock normals have been calculated from both the model of Greenstadt et al. [1990] at the positions of shock crossing and coplanarity results obtainable from the locally varying, hence not very reliably represented, downstream components. For pulses and the upstream fields in which they occurred, the normals were calculated for the spacecraft locations at the times of nearest corresponding shock crossings, but directions of the solar wind's IMF were averaged for intervals just upstream from significant foreshock activity in an attempt to evade changes in the measured field components influenced by the foreshock itself, particularly its pulses. No ϑ_{Bn} should be taken as an exact value, but only as confirmation that the corresponding shock/foreshock system was as Q_{\parallel} at the closest time of undisturbed IMF as its deeper signature indicated.

Most of the examples are represented as paired time plots of field magnitude and normal angle. Samples from both ISEE 1 and 2 are shown, some for the same data intervals, in which somewhat dissimilar records from the separated spacecraft offer semi-independent results.

Examples

Shock context and crossings

Figure 1 displays a compressed plot of foreshock phenomena "typical" of a long enough (> 15 min.) approach to a Q_{\parallel} shock to suggest relatively steady upstream conditions. Outside the figure to the left, $\vartheta_{Bn} \approx 19^{\circ}$ upstream from major excursions of \mathbf{B} in the foreshock. We see increases in field magnitude, wave frequency, wave amplitude, pulse amplitude, and pulse incidence as ISEE 1 nears the magnetosheath at the right of the figure. By "pulses" throughout this report we mean temporary rises in B to levels comparable to downstream

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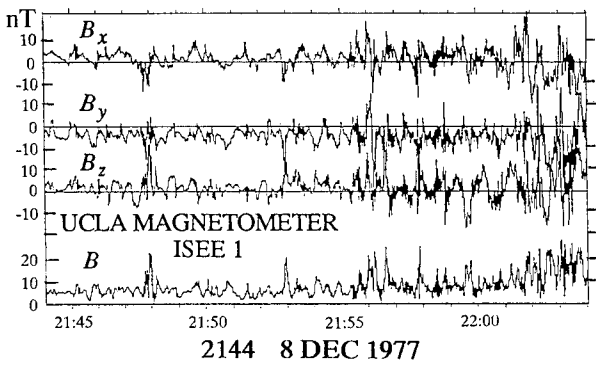


Fig. 1. Twenty minute section of magnetic field leading to Q_{\parallel} bow shock crossing just before 2202. Time given at the bottom is for the beginning of the plot in this and following figures and panels.

average or even overshoot values, as in strong ($M_A > 3$) Q_{\perp} shocks [Livesey et al., 1982], but adjacent to lower average field magnitudes before and after their occurrence. All the cases of this study were strong shocks, as indicated by their locations near the nose of the average hyperbolic model [Greenstadt et al., 1990]. "Crossings" were identified by sustained changes in B in which the field maintained distinguishable levels of average upstream and downstream values.

A shock "crossing" is illustrated in detail in Figure 2, showing the elevation of ϑ_{Bn} in the upper panel to Q_{\perp} values well outside the shock "ramp," which was well within an envelope of average Q_{\perp} field orientation that extended to about 0420 upstream, after which average Q_{\parallel} ϑ_{Bn} prevailed amid large Q_{\perp} excursions. The "emergence" from the shock by ISEE 1, which seems ambiguous, was much clearer at the corresponding ISEE 2 crossing, but without the upstream pattern of ϑ_{Bn} we want to illustrate. The distant value of ϑ_{Bn} for this shock is 27° .

Upstream Pulses

Figure 2 illustrates two general characteristics of Q_{\parallel} foreshocks: First, large individual pulses, as at 0404 and 0405 (arrows), tended to correlate with Q_{\perp} values of ϑ_{Bn} even when significant other portions of the perturbations' field orientations were in the Q_{\parallel} regime. Second, the transverse components of the ambient waves were so

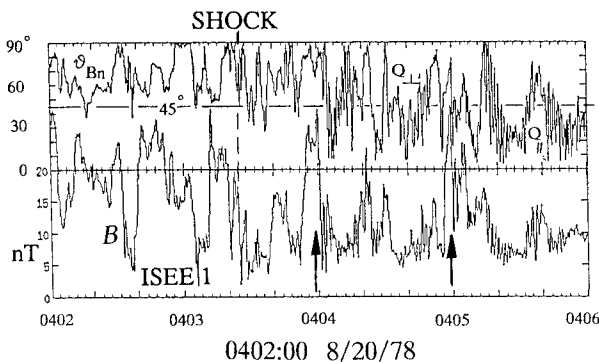


Fig. 2. A Q_{\parallel} bow shock crossing represented by the ambient field magnetude B and the field-normal angle ϑ_{Bn} . Arrows mark major upstream pulses.

large relative to the local ambient field that the field direction often differed significantly from its unaffected (i.e. distant, wavefree) Q_{\parallel} orientation even when the field magnitude displayed no pulses rising to downstream-like levels. That is, ϑ_{Bn} often crossed over the approximate 45° division between Q_{\parallel} and Q_{\perp} field orientation, and extreme values of ϑ_{Bn} near 90° were by no means confined to intervals in which B made extreme excursions to high values. The plots of Figure 2 are representative of the generality of field signatures outside but near to our Q_{\parallel} bow shock crossings.

Figures 3 and 4 present 11 samples of individual pulses of various shapes and sizes and their corresponding ϑ_{Bn} environments. The plots of B are dashed, the plots of ϑ_{Bn} are solid. All the time scales and their 10s tic marks are the same; distances of, and distances between, the satellites at the times of observation are, along with upstream ϑ_{Bn} , given in Table 1.

While there is no fixed quantitative form or relationship between the field and angle enhancements, the tendency for the shock or overshoot elevations of pulses to occur within intervals in which the shock normal angle was Q_{\perp} is apparent in all these cases. All pulses selected here were "isolated" magnetically in that none was embedded within contiguous trains of high amplitude field deviations, but were preceded and followed by average to moderate sized waves for intervals longer than the pulse durations themselves. We suspect many of our simpler pulses, lasting 10-20s, could be designated as "isolated" SLAMS [Schwartz and Burgess, 1991], but it is not possible to cross-identify the two observations of pulses at this time.

Figure 4 is devoted to four paired ISEE 1-2 examples

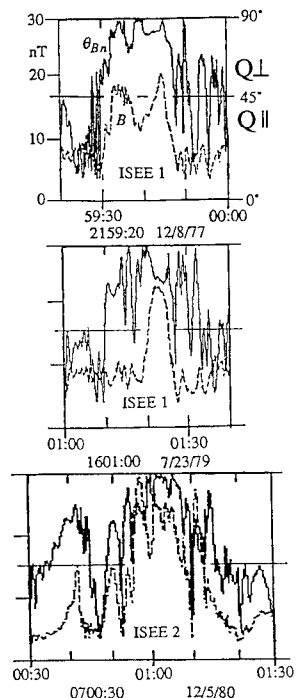


Fig. 3. Three single-spacecraft observations of upstream pulses surrounded by high, Q_{\perp} - ϑ_{Bn} . Vertical scales and labels applicable to all three cases are indicated in the top panel; all time tics are separated by 10s.

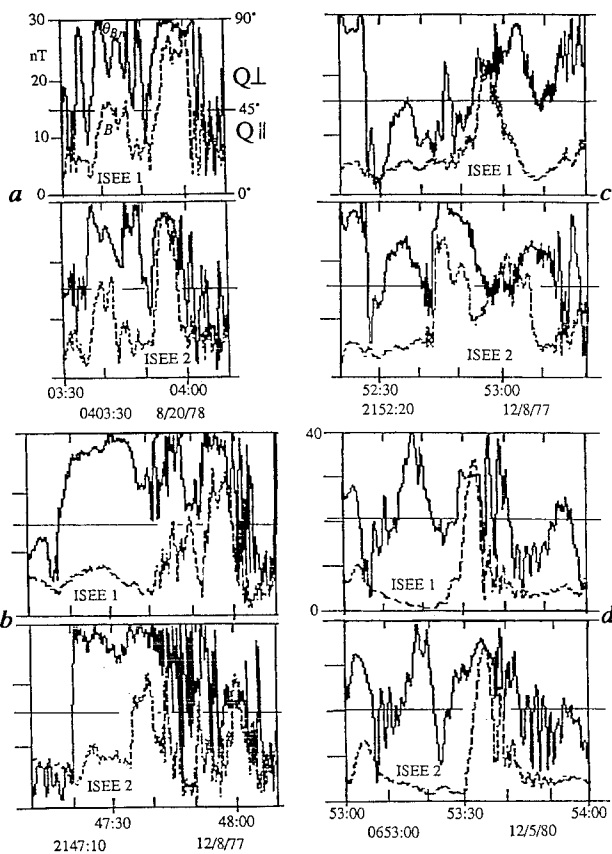


Fig. 4. Four paired observations of upstream pulse events. Notation as in Fig. 3 with the exception that the vertical scale is compressed (*d*).

set on a common time axis, to call attention to the frequently differing profiles of the pulses at the two separated spacecraft. Paired pulse events caught by separated ISEE 1,2 observations should allow us to determine the direction of travel of pulses by measuring the delay between identifiable markers in the field patterns at the two spacecraft. However, the two pairs from December 8, 1977 show clearly the impossibility of finding duplicate markers in some cases. In these examples, the pulse shapes are so dissimilar that we cannot identify analogous phases of the B excursions at the two satellites. In striking contrast, the pulse forms at 0653 on December 5, 1980, were very similar, each consisting of a tall pulse followed by a series of damped waves in the spacecraft frame. Qualitative similarities can be seen in the two ϑ_{Bn} patterns as well.

Despite differences from case to case among the four paired examples, one feature was common to all of them: The pattern of elevated field began first at the upstream

spacecraft. Thus the pulse event "units" as a whole seem to have been convecting downstream, a property common to upstream ULF waves [Hoppe and Russell, 1983] and enlarged perturbations examined in earlier studies [Thomsen et al. 1990]. This means that the time history of each pulse, as plotted, is the reverse of the sequence in which the solar wind actually encountered it, i.e., the trailing edge of each pulse's signature in the figures was its upstream side. We think the significance of our observations is that enlarged ϑ_{Bn} preceded the corresponding enhancements of B in the solar wind frame.

Although pulse shape was sometimes preserved with notable fidelity over the one to two second delay and 200 to 500 km distance between the observation points (Figure 4, *c* and *d*), these small separations were sufficient in other cases (*a* and *b*) to allow the pulse signatures to differ appreciably from one another. Either the pulses were evolving rapidly between detections by the two spacecraft or they were exhibiting more or less fixed distinctions along nonuniform wavefronts in space.

Discussion

Summary

Not all elevations of B with amplitudes above those of local "background" waves correlate with high ϑ_{Bn} . Merely moderate wave enhancements or very brief amplitude spikes have not been consistently accompanied by any temporary change of field direction in the events examined so far. But selected events that either endured for several seconds or reached peaks two to three times the average local B , or both, did satisfy the correlation at both spacecraft. Thus there appears to be a class of upstream Q_{\parallel} pulses, such as those illustrated here, that coexist only with, and are preceded in the solar wind frame by, locally Q_{\perp} - ϑ_{Bn} .

Linked rotations and elevations of B

The Rankine-Hugoniot (R-H) MHD jump conditions [DeHoffman and Teller, 1950] require that the component of B tangent to a shock be enlarged downstream, tending necessarily to make the downstream field more "perpendicular" than its upstream, unshocked counterpart. Conversely, a large, purely transverse wave superimposed on a steady background B_0 necessarily yields a resultant $B > B_0$.

However, "the structure of the dissipation layer is not describable by ideal MHD," [Kennel et al., 1985], a deficiency that applies to the ULF waves and irregularities characterizing the details of Q_{\parallel} transitions, and the instantaneous properties within the various features. Moreover, the interiors of our pulses are not necessarily shocked solar wind, unless they differ appreciably from the "isolated SLAMS" of Schwartz et al. [1992]. Also, the pulses are not just waves, and our data clearly show Q_{\perp} excursions of ϑ_{Bn} that do not correspond to pulse summits. In our figures, there were many more major rotations of B than wave maxima, nonshocklike compressions, or shocklike pulses. Thus there's no routine MHD or geometric link between the magnitude and direction of B among our more extreme foreshock elements.

TABLE 1

Date	R(X,Y,Z) R_E	$\delta R(\delta X, \delta Y, \delta Z)$ km	ϑ_{Bn}
8Dec77	8.7,-13.3, 6.9	-372, 134, 258	19°
20Aug7	13.2, 6.0, 5.8	-240,-107,-149	27°
23Jul79	1.0, 16.5, -1	432, 917, 161	41°
5Dec80	11.3,-10.5,-3.3	173,-480, 22	11°

The confirmed phenomenology of ϑ_{Bn} in the natural Q_{\parallel} bow shock in space shown here and in earlier reports [Greenstadt, 1985; Greenstadt and Mellott, 1985;], when combined with subsequent numerical simulations [Burgess, 1989; Thomas et al., 1990; Winske et al., 1990; Scholer and Burgess, 1992], suggests a crude, nonfluid, conceptual picture of pulses in the Q_{\parallel} environment of the bow shock's physics at Mach numbers about 5, i.e., under conditions typical of the subsolar region.

Tentative model

The sporadic appearance of reflected beams around the Q_{\parallel} bow shock has been reported by Gosling et al. [1982] and Onsager et al. [1990]. This phenomenon is not surprising if the actual up-to-downstream crossing is often or always locally Q_{\perp} , as in Figure 2, since this is the geometry in which such beams form a steady ion, plasma wave, and magnetic "foot" in front of regular Q_{\perp} shocks.

In our Figure 1, waves of small to moderate amplitude are not seen to have "grown" gradually into pulses and shock fronts, but to have been punctuated with pulses, albeit with increasing incidence as the magnetosheath was approached. In the computer laboratory, some of the stacked-wave time profiles in the simulations cited above have also shown that the enlargement of upstream waves to re-form new shock fronts is selective. In this respect, nature and the one-dimensional models are compatible. It thus appears that in the computer, as in space, there is a selection by the plasma of which waves become enlarged, and we may combine the satellite and simulation data into a plausible scenario. At the bow shock, as in the simulations of Scholer and Burgess [1992], when the crests of waves with $\vartheta_{Bn} > 40^{\circ}$ (or more) encounter the outer limit of the reflected beam, they form a positive feedback loop leading eventually to rising ϑ_{Bn} , growing field strength, and ultimately formation of a new shock front.

A comparable, not necessarily inconsistent, scenario invoking a gradient of diffuse rather than reflected foreshock ions to motivate shock reformation *via* SLAMS, was proposed by Giacalone et al. [1993]. Further study of other plasma parameters and Q_{\parallel} phenomena is essential.

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