Initial ISEE Observations of the Bow Shock.

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Summary. — ISEE 1 and 2 magnetic-field profiles across three terrestrial bow shock crossings are shown to illustrate the control of the bow shock structure and upstream waves by solar-wind conditions, especially by the direction of the interplanetary field. The quasi-perpendicular shocks examined have thicknesses of the order of a ion inertial length. Upstream waves observed for field directions of about 45° to the shock normal are observed to be carried back towards the bow shock by the solar wind, while propagating upstream at what appears to be the magnetosonic velocity. These studies are continuing.

1. – Introduction.

The goals of the International Sun-Earth Explorer program are many and varied. We are attempting to probe the solar wind and magnetosphere with new and improved instrumentation. We are attempting to unfold temporal from spatial changes and to measure velocities, thicknesses and current densities of the various boundaries in and around the magnetosphere. To do this ISEE 1 and ISEE 2 were launched into very nearly identical orbits with apogees at 23 \( R_E \), carrying in some cases identical instrumentation. The bow shock is perhaps the thinnest and the fastest moving of these boundaries. It may also be the most sensitive to external conditions.

Perhaps the most important single parameter which controls the structure of the bow shock is the direction of the interplanetary magnetic field. Figure 1
shows an artist's conception of what the terrestrial bow shock would look like if we could see the magnitude of the magnetic field. In regions in which the interplanetary magnetic field is at right angles to the local shock normal

Fig. 1. – An artist's conception of the dependence of the structure of the Earth's bow shock as a function of the direction of the interplanetary magnetic field relative to the local shock normal. The various islands represent guesses as to the angular distribution functions of protons in the various regions (1).

the profile is quite regular. Where the interplanetary field is nearly parallel to the shock normal, the structure is very irregular. We call the former type of shocks perpendicular shocks and we call the latter parallel shocks. Between these two extremes we classify shocks as either quasi-perpendicular or

quasi-parallel depending on whether the angle between the field and shock normal is greater than or less than about 50° (1).

The Earth's bow shock is also sensitive to the Mach number and beta of the solar wind. Shocks that are both low in Mach number and low in beta have been called laminar shocks; shocks high in both Mach number and beta are called turbulent. In between these two extremes low-Mach-number, high-beta shocks have been called quasi-turbulent and high-Mach-number, low-beta shocks have been called quasi-laminar (2). Laminar shocks have been studied extensively by Greenstadt et al. (3) and Fairfield and Feldman (4). Quasi-parallel shocks have been investigated by Greenstadt et al. (5) and very-high-beta shocks by Formisano et al. (6). However, these studies were limited to single satellite encounters with the bow shock or to chance nearly simultaneous crossings at widely separated shock locations. The ISEE 1 and 2 measurements, on the other hand, permit systematic time-of-flight determinations of shock velocities and allow us to quantify our earlier classifications. Thus it is instructive to examine shocks of each of these types with the ISEE data to further our understanding of them. At this writing our study is only just beginning and we have not yet assembled examples of the full spectrum of shock behaviour. Herein we examine shock encounters on three separate orbits. The first two shocks are quasi-perpendicular shocks; one is quasi-turbulent and one turbulent. The third shock is also turbulent, but much closer to being classified as a quasi-parallel shock. An instrument description and more examples of shock encounters can be found in (7) and a complementary treatment of interplanetary shocks in (8).

2. - ISEE observations.

2'1. Shocks of October 27, 1977. - Figure 2 shows the magnetic-field strength measured at ISEE 1 and 2 from 1844-1907 UT on October 27, 1977. The two spacecraft were separated by 565 km at this time and situated 8.82R_e in front

of the Earth and 12.29\(R_E\) from the Earth-Sun line. The interplanetary field was strong, 12.8 \(\gamma\), and steady. The angle between upstream field and shock normal was 68° and the separation along the shock normal was 548 km. The Alfvén Mach number was 4.5, the magnetosonic Mach number 3.6 and the solar wind \(\beta\) 0.7, by using preliminary solar-wind data by courtesy of BAME and PASCHMANN. Since the magnetosonic Mach number was greater than 3

![Magnetic-field strength (\(\gamma\)) across two shock crossings on October 27, 1977, as measured on ISEE 1 and 2. The angle between the upstream magnetic field and local shock normal was 68°.](image)

and the solar-wind beta less than 1, we would presently classify this shock as quasi-turbulent. One of the areas of research that we intend to pursue in future ISEE investigations is where best to place the dividing lines between the various classifications.

There are two sets of crossings here. The delay between the first set of crossings at the two spacecraft is 94 s and between the second is 53 s, corresponding to velocities of 5.8 and 10.4 km/s. Determining a thickness is not unambiguous and is somewhat definition dependent. There were clearly non-stationary waves present, beginning at the base of the shock, whose amplitude was a significant fraction of the shock jump. These waves had a period of about 5 s, half of the apparent thickness of the shock. If we approximate the shock crossing with a linear ramp, the average crossing time was 10 s, corresponding to a thickness of 80 km. The ion density at this time was 15 \(cm^3\), corresponding to a ion inertial length of 60 km. Thus the shock thickness was the order of 1 ion inertial length.

Figure 3 shows the three vector components of the field and the field magnitude as measured by ISEE 1 in shock normal co-ordinates. The components
Fig. 3. – ISEE 1 magnetic-field measurements (γ) in shock normal co-ordinates across two bow shock crossings on October 27, 1977.

orthogonal to the main field jump clearly show the rapid build-up of the 5 s wave. In the bottom panel we have plotted an exponential decay on the total field trace at each of the shocks. The decay times of 30 and 40 km are slightly less than a ion inertial length. A noticeable feature of these shocks is an «overshoot» in the field strength immediately behind the shock in which field strengths were achieved which were much higher than magnetosheath fields further from the shock. The overshoot region seems to be followed by a slight depression in the field magnitude. However, this feature was not as pronounced as the overshoot. Preliminary examination of particle data indicates that the electron density and magnetic-field strength are positively correlated in the overshoot region (9). Thus the overshoot appears to have some fundamental

role in the physics of at least this type of bow shock. The average thickness of this region was 160 km, slightly less than 3 ion inertial lengths. The wave levels are more intense just behind the shock than further downstream. Just behind the shock the waves in the total field strength were 25% of the field strength. Later in the region, not plotted in fig. 3, they are only 5% of the field strength.

2'2. Shock of November 5, 1977. — Figure 4 shows the magnetic-field strength measured at ISEE 1 and 2 from 1319-1326 UT on November 5, 1977. The spacecraft were separated by 277 km and were 13.18\(R_E\) in front of the Earth and 8.30\(R_E\) from the Sun-Earth line. The interplanetary-field strength was 6.9\(\gamma\). The angle between the upstream field and shock normal was 61°, and the separation along the shock normal was 228 km. The Alfvén Mach number was 6.0, the magnetosonic Mach number was 4.0 and the solar-wind \(\beta\) was 1.6, if we use preliminary solar-wind data by courtesy of BAME and PASCHMANN. Since the magnetosonic Mach number was greater than 3 and the solar-wind beta greater than 1, we would classify this shock as turbulent.

There are three distinct regions of upstream behaviour in fig. 4. First, prior to 1320 there were low-frequency (20 s period) waves present. From 1320 to 1321:15 there were essentially no waves. Then, in continuing to the shock, there were high-frequency waves with about a 1 s period. Each of these different regions was associated with a different direction of the interplanetary magnetic field relative to the shock normal. The low-frequency waves were

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**Fig. 4.** — Magnetic-field strength (\(\gamma\)) at ISEE 1 and 2 measured across the bow shock on November 5, 1977. The angle between the local shock normal and the upstream magnetic field just prior to the shock was 61°.
associated with an angle between upstream field and shock normal of 46.5°, the high-frequency waves with an angle of 61° and the quiet field with an angle of 69°.

The shock required 33 s to move from ISEE 1 to ISEE 2, corresponding to a velocity of 6.9 km/s. Again the thickness of the shock is somewhat ambiguous because of the presence of nonstationary waves on the shock ramp. Using a linear ramp approximation, we obtain a crossing time of about 10 s, or a thickness of 70 km, which is a little less than 1 ion inertial length. Figure 5 shows the ISEE 2 data in shock normal co-ordinates. The exponential fit gives an e-folding length of 40 km. The apparent wavelength of the waves on the

![Graph showing magnetic-field measurements](image)

Fig. 5. – ISEE 2 magnetic-field measurements (γ) across the bow shock in shock normal co-ordinates for the November 5 shock.

shock transition is 24 km. However, these waves do not appear to be stationary in the shock frame. There was an "overshoot" in the field magnitude immediately behind the shock, but its duration and appearance were quite different in the two records. The ISEE 1 overshoot lasted 12 s, followed by a sudden decrease in the field magnitude. The duration of the ISEE 2 overshoot appears to last about 50 s and tapers off more gradually. As before, both satellites recorded a decrease in field strength below later magnetosheath values.
The upstream waves observed from 1318 to 1320 were associated with a field direction of 47° to the shock normal. Minimum-variance analysis of these waves reveals a wave normal only 3° from the shock normal. The waves are seen first at ISEE 2, about 1 s before being seen at ISEE 1. The separation of the spacecraft along the wave normal was 221 km and the component of the solar-wind velocity was 305 km/s. Since the apparent wave velocity was 220 km/s from ISEE 2 to ISEE 1, the wave velocity was about 85 km/s away from the shock in the solar-wind frame; this is slightly greater than the local Alfvén velocity and approximately equal to the magnetosonic velocity. The apparent sense of polarization was left-handed. Hence these waves are, in fact, right-handed waves propagating upstream against the solar-wind flow, but being convected downstream towards the shock by the solar wind.

Fig. 6. – ISEE 1 and 2 measurements of the field strength (γ) across the bow shock on November 10, 1977. The angle between the local shock normal and the upstream magnetic field was 53°.
2.3. Shock of November 10, 1977. – Figure 6 shows the magnetic-field strength measured at ISEE1 and 2 from 1059 to 1104 UT on November 10, 1977. The two spacecraft were separated by 160 km at this time and situated 10.99\(R_E\) in front of the Earth and 6.55\(R_E\) from the Earth-Sun line. The interplanetary-field strength was typical, 6.5 \(\gamma\), but irregular. The angle between the upstream field and the shock normal was about 53° and the separation along the shock normal was 122 km. The Alfvén Mach number was 6.0, the magnetosonic Mach number 3.3 and the solar-wind beta 3.1, by using preliminary solar-wind data by courtesy of BAME and PASCHMANN. This shock is a turbulent shock according to our classification and close to the dividing line between quasi-parallel and quasi-perpendicular.

Several characteristics of these shocks are immediately evident. First, the magnetic field is highly irregular behind the shock and, second, the peak field strengths are very much larger than the upstream field. One peak seen on both ISEE 1 and 2 reaches 57 \(\gamma\), a factor of 9 greater than the average upstream field. Moreover, in general, the field variations are quite different at the two locations, even though they are much closer than in the two previous cases. However, the general behaviour of the field is quite similar at ISEE 1 and 2. Finally, we note that the shock was crossed almost simultaneously by the two spacecraft. However, the non–time-stationary character of the data makes any velocity determination ambiguous.

3. – Discussion.

We have presented herein only a few examples of the ISEE 1 and 2 shock data. We are now in the process of analysing many more shock crossings under a wide variety of plasma conditions. These data certainly suggest that varying conditions in the solar wind intimately control the structure of the bow shock as expected from earlier studies. However, with the ISEE spacecraft we should be able to quantify this control. Further, even though we have only mentioned the correlations here, many of the plasma instruments on ISEE have high enough time resolution that we can correlate the particle behaviour with that of the magnetic field through the shock. Also important in these studies are the plasma wave measurements of comparable temporal resolution. It is also quite interesting that in the shocks studied thus far the thickness has been comparable to a ion inertial length. Whether this thickness will be characteristic of shocks under a variety of solar-wind conditions remains to be tested.

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● RIASSUNTO (*)

Si mostrano i profili del campo magnetico di ISEE 1 and 2 attraverso tre incrci del- l'onda d'urto terrestre per illustrare il controllo della struttura dell'onda d'urto e delle onde a monte da parte delle condizioni del vento solare, specialmente da parte della direzione del campo interplanetario. Gli urti quasi perpendicolari esaminati hanno spessori dell'ordine di una lunghezza ionica inerziale. Si osserva che onde a monte osservate per direzioni di campo di circa 45° rispetto alla perpendicolare all'urto sono riportate indietro verso l'onda d'urto dal vento solare, mentre si propagano a monte di ciò che appare essere la velocità magnetosonica. Questi studi continuano.

(*) Traduzione a cura della Redazione.

Начальные наблюдения ударной волнс sжатия в рамках международных исследований по программе «Солнце-Земля».

Резюме (*). — Показывается, что профили магнитных полей ISEE 1 и ISEE 2 поперек трех пересечений Земных ударных волн sжатия иллюстрируют влияние солнечного ветра и, особенно, направления межпланетного магнитного поля на структуру ударной волны сжатия и на волны, направленные против потока. Исследованные квази-перпендикулярные ударные волны имеют толщину порядка иононой инерциальной длины. Обнаружено, что наблюденные волны, направленные против потока, для направлений поля около 45° к нормали к ударной волне увлечены солнечным ветром в противоположном направлении к ударной волне sжатия. Эти исследования продолжаются.

(*) Переведено редакцией.