Initial Observations of Interplanetary Shocks by STEREO

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Abstract. Initial observations by the magnetometer on the twin STEREO spacecraft reveal much about shock structure and evolution in the solar wind. Alignments of STEREO with Venus Express reveal that none of the shocks associated with stream interactions and observed with the STEREO spacecraft at 1 AU were present in the solar wind at 0.7 AU, indicating that the region between Venus and Earth is an incubator for interplanetary shocks. We find examples from the STEREO data of the coalescing of weak shocks to form stronger shocks. These weak shocks frequently exhibit wave structure upstream and downstream of the shock inconsistent with early ideas of the formation of these wave trains.

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INTRODUCTION

The launch of the twin STEREO spacecraft in October 2006 has provided us with a continuous monitor of the solar wind away from the influence of a nearby planetary shock giving us over two measurement-years at this writing. In this report, we discuss some of the initial findings on interplanetary shocks enabled by the STEREO magnetic measurements [1]. STEREO was launched during an extended solar minimum in which few ICMEs passed either spacecraft, producing no or only weak shocks, with only one exception. Many shocks were observed associated with the interactions of fast and slow streams. These too were weak.

Most weak shocks fall into the class called laminar shocks, where dispersion limits non-linear steepening, and a trailing or leading wavetrain is generated [2]. Dissipation is expected to occur via the process that damps the wavetrain. Unfortunately, even back in 1973, it was realized that the observed shock profiles "were often quite different from dispersive wave trains being rather monotonic instead of oscillatory, thus indicating the presence of efficient collisionless dissipation processes" [2]. The classical discussion of laminar shocks considers two types of dispersion: type 1 in which the wave velocity

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decreases with increasing frequency, and type 2 in which it increases. Perpendicular magnetosonic shocks are given as the candidate for the first type, and oblique shocks with waves in the low frequency part of the whistler branch are given as the candidate for the second type. We should note that the scale length of the first shock type is the electron inertial length and of the second type is the ion inertial length that differ by a factor of $(m_p/m_e)^{1/2}$ or 43. The downstream profile of the type 1 shock is expected to look like a damped oscillating soliton, asymptoting to the downstream value. The upstream profile of the oblique shock should look like a damped sinusoid about the upstream value. In fact, we have only ever observed one perpendicular shock [3], and that shock was not laminar so it did not resemble a damped soliton. All our laminar shocks are oblique type 2 shocks, some of which very much resemble the expected profile, but many do not. Thus laminar shock theory must be taken beyond the work of [4], [2], [5], and [6]. This view was also recently expressed by [7], but rather than saying that we have found new types of shocks with STEREO as was said about the Venus Express observations [7], we feel instead that laminar shocks have never been fully understood. STEREO observations, especially when coupled to the power of modern hybrid simulations, promise to provide that understanding.

In this report we begin this analysis by examining two aspects of these laminar shocks: their evolution in the region from 0.7 to 1.0 AU, and the behavior of their leading and trailing wave trains.

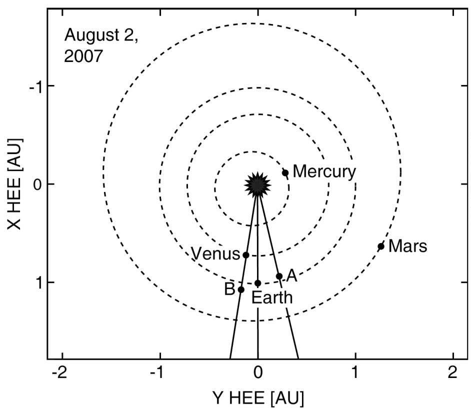


FIGURE 1a. Projection of the positions of Venus, Earth, Mars, STEREO A and B on the ecliptic plane during the STEREO B alignment with Venus on August 2, 2007.

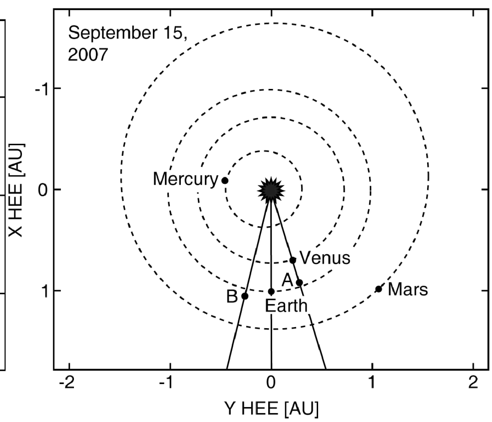


FIGURE 1b. Projection of the positions of Venus, Earth, Mars, STEREO A and B on the ecliptic plane during the STEREO A alignment with Venus on September 15, 2007.

SHOCK EVOLUTION

In August and September 2007, Venus Express at 0.7 AU was aligned first with STEREO B and then STEREO A as it circled the Sun in its 225-day orbit. These conjunctions are illustrated in Fig. 1a and b. Venus Express one-second magnetic field data were examined for 30 days around each conjunction, but no shocks were detected. In contrast, at 1 AU, four shocks were found at STEREO A, and five shocks at STEREO B, all associated with stream interactions, except one. Shocks at stream interactions occur as the fast-mode wave speed drops with heliocentric distance and the velocity jump across the stream interface exceeds the speed of this compressional wave allowing shocks to form. Conventional wisdom is that this process occurs beyond the Earth's orbit and while this is certainly true at some level, many shocks arise between 0.7 AU and 1 AU. A recent study of shocks observed from 1995-2006 during solar cycle 23, an update of earlier work [8], found that 26% of the stream interactions were accompanied by shocks at 1 AU. During the period from March to October 2007, STEREO A and B found that 42% of the stream interactions were accompanied by shocks. We do not know the reason for this significantly larger number. It is possible that the present solar minimum period is unusual in some way, that the separation of STEREO A and B from the Earth has allowed more sensitive detections or that the accuracy and greater time resolution of the STEREO magnetic field observations has allowed more certain identifications. Regardless of the reason, it is clear that the region from 0.7 AU to 1.0 AU is an incubator for collisionless shocks.

A long standing paradigm of shock formation [5] is that shocks strengthen by the coalescence of successive weak shocks overtaking each other. This idea is confirmed in the STEREO data and one example of several found in the STEREO observations is shown in Fig. 2, in which two weak shocks are seen in a fast-slow stream interaction region only 30 minutes apart. Eventually the second shock will overtake the leading shock and a single stronger shock will form. Figures 3a and b show the magnetic field components across these two shocks in shock-normal coordinates. This demonstrates that these sharp changes are indeed shocks as they show characteristic shock waveforms and satisfy Rankine-Hugoniot relations.

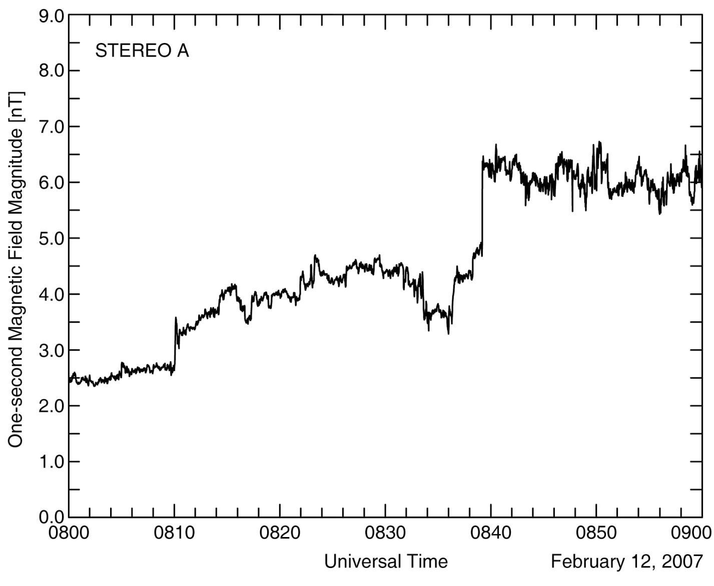
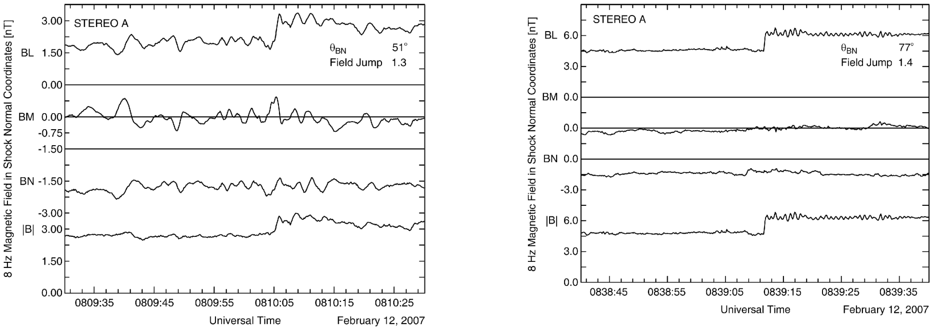


FIGURE 2. One-second measurement of the magnetic field strength at STEREO A on the leading edge of a stream interaction region on February 12, 2007. The two sharp increases in the magnetic field are weak shocks each accommodating part of the expected rise in velocity at the stream interaction.



FIGURES 3a, b. Eight-Hertz measurements of the magnetic field across the shocks seen in Fig. 2 rotated into shock normal coordinates, in which the field in the B_M direction is zero both upstream and downstream. B_N is constant and along the normal and the B_L component includes the jump of the magnetic field. The characteristic changes in the magnetic field illustrate that these discontinuities are both weak shocks.

LEADING AND TRAILING WAVE STRUCTURE

Laminar shocks are low-Mach number, low-beta shocks in which wave growth and damping provide the dissipation required by the Rankine-Hugoniot conditions. Early shock theories [2, 4, 6], held that wave trains would be either upstream or downstream. The ISEE mission found a rich array of upstream and downstream waves generated at the shock ordered by the angle of the magnetic field to the shock normal θ_{BN} and by the Mach number of the shock [9]. In particular, M.H. Farris found that compressional downstream fluctuations at shocks near the critical Mach number were associated with gyrophased motion of protons bunched at the shock ramp. Recent Venus Express observations show that such downstream compressions are observed even at a weak laminar shock, are inconsistent with the original shock theory, and may be explained by gyrophased motion of ions [2]. The Venus Express study suggested that this behavior is rare but STEREO reveals that such simultaneous upstream and downstream waves are common. Furthermore, downstream compressive waves at weak shocks are very common.

Figures 4 and 5 illustrate shocks with predominantly upstream or downstream waves. The shocks have been chosen to have similar field jumps, but they have different θ_{BN} angles. The more parallel shock in Fig. 4 has the more extensive upstream wave train and the less extensive downstream waves. The upstream wave does not propagate along the shock normal as it is seen in the B_N component and it is compressional. Except for a weak overshoot behind the shock, the downstream wave is mainly transverse.

In Figure 5, the more perpendicular shock has a compressional wave downstream and a weak mainly transverse wave upstream extending only a short distance into the pre-shock plasma. While there are shocks which nearly obey the early paradigm, many shocks clearly violate it. Figure 6 shows a moderately strong quasi-perpendicular shock that has both significant upstream and downstream wave trains. The downstream and upstream wave trains have both transverse and compressional components. Figure 7 shows a weak quasi-perpendicular shock with a field jump of only 1.4. Again, the upstream and downstream wave trains are extensive and are neither completely transverse nor compressional.

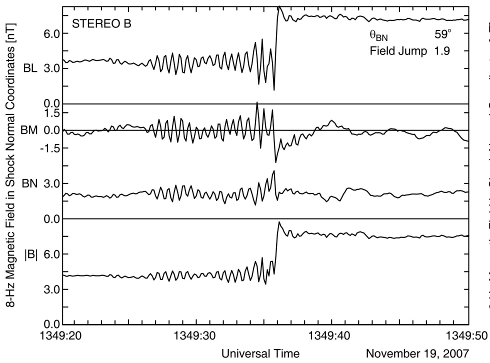


FIGURE 4. Eight-Hertz magnetic field measurements in shock normal coordinates from STEREO B on November 19, 2007. This example shows a wavetrain extending most strongly upstream.

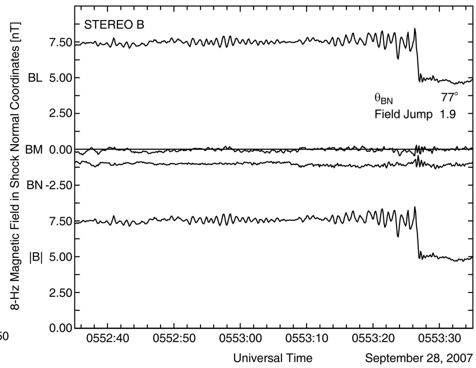


FIGURE 5. Eight-Hertz field measurements in shock normal coordinates from STEREO B on September 28, 2007. This example shows a wave train principally extending downstream. The main difference between this case and the one in Fig. 4 is the higher angle of the magnetic field to the shock normal. The upstream beta for this shock was unity.

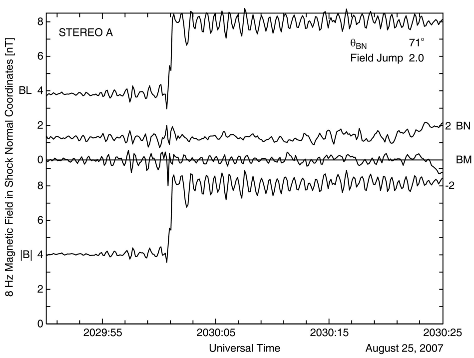


FIGURE 6. Eight-Hertz magnetic field measurements across an interplanetary shock in shock normal coordinates obtained by STEREO A on August 25, 2007. This example shows significant wave activity both upstream and downstream with dominant waves downstream. The upstream beta for this shock was five.

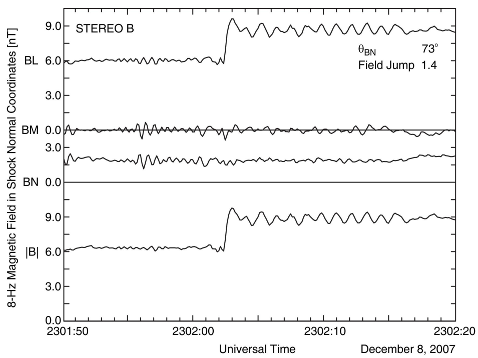


FIGURE 7. Eight-Hertz magnetic field measurements across an interplanetary shock in shock normal coordinates obtained by STEREO B on December 8, 2007. This example is a much weaker shock than in Fig. 6 and still shows both upstream and downstream wave activity at a similar θ_{BN} angle. The upstream beta for this shock was two.

SUMMARY AND CONCLUSIONS

The initial year of operation of the STEREO spacecraft has revealed numerous weak shocks near 1 AU, most associated with stream interactions. An examination of measurements by Venus Express during conjunctions with STEREO A and B shows that these shocks arise at distances greater than 0.7 AU. Some shocks at 1 AU occur in pairs with the trailing shock apparently overtaking the leading shock, eventually resulting in a single stronger shock. Some confusion apparently exists on the cause of the waves seen upstream and downstream from the shock. These wave trains are not exclusive. A wide range of shock parameters result in waves simultaneously moving into the unshocked solar wind and also moving downstream. These observations appear to invalidate the original theory of these laminar shocks. Future work will examine if these waves are associated with pressure anisotropies generated by the shock or with the phase bunching of ions in transiting the ramp.

ACKNOWLEDGMENTS

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