GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L02103, doi:10.1029/2008GL036337, 2009

STEREO observations of shock formation in the solar wind

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Received 14 October 2008; revised 11 December 2008; accepted 16 December 2008; published 24 January 2009.

[1] During solar minimum, the majority of shocks observed at 1 AU are associated with interactions between fast and slow streams, appearing as the pressure ridge between the streams narrows, and as the fast mode speed becomes smaller than the velocity jump between streams. Shocks are believed to strengthen when following shock waves catch up with the leading shock. STEREO observations confirm this behavior for very weak shocks. We can also put limits on the location of the shock-forming region by examining the periods of alignment between Venus and STEREO. In a period in which we see nine shocks at 1 AU, we see no shocks at 0.72 AU. Hence, stream interactions from 0.72 AU to 1 AU are responsible for the development of most of the shocks observed at 1 AU during solar minimum. **Citation:** Russell, C. T., L. K. Jian, X. Blanco Cano, J. G. Luhmann, and T. L. Zhang (2009), STEREO observations of shock formation in the solar wind, *Geophys. Res. Lett.*, *36*, L02103, doi:10.1029/2008GL036337.

1. Introduction

[2] The classical theory of shock formation [e.g., *Kantrowitz and Petschek*, 1966] states that shocks strengthen when following shocks catch up with the leading shock. An ideal place to study shock formation is in stream interactions near 1 AU. Stream interactions persist throughout the solar cycle, changing only slightly with solar cycle phase [*Jian et al.*, 2006]. The launch of STEREO at solar minimum provides a rich opportunity to study the structure of low Mach-number shocks and how these shocks form and steepen. STEREO A and B [*Kaiser et al.*, 2008] carry, among other sensors, a magnetometer [*Acuña et al.*, 2008] that returns vector field measurements every 125 ms, and include a burst-mode capability of 32 Hz. They also carry a solar wind plasma analyzer that returns measurements once per minute [*Galvin et al.*, 2008]. At this writing, almost two years of solar wind measurements are available from STEREO A and STEREO B, and the Sun remains in an unusual solar minimum. An additional measurement point is provided by the Venus Express spacecraft at 0.72 AU that carries a fluxgate magnetometer with similar cadence [*Zhang et al.*, 2006]. In the period since launch, both STEREO A and B have each moved through a solar wind conjunction with Venus Express. We can use these conjunctions to constrain where interplanetary shocks are born.

2. Shock Steepening

[3] Figure 1 shows a pair of shocks on February 12, 2007, observed in 1-second data. Since shocks are expected to be seen about once every month at 1 AU [*Jian et al.*, 2006], observing two within less than 1 hour indicates that these shocks are related. In fact, we expect the following shock, traveling in a stronger magnetic field, to be traveling faster than the leading shock. These two jumps in B are indeed shocks as revealed by the 8-Hz data shown in Figures 2 and 3 in shock normal coordinates. This coordinate system is constructed from average magnetic fields upstream and downstream from the shock jump. Since the upstream and downstream fields and the shock normal must be coplanar, and since the condition that the divergence of B must be zero means that the field component along the shock normal does not change, these two averages can be used to find the shock normal. Both shocks have characteristic shock behavior, including a single direction containing a sharp jump in the magnetic field that does not cross zero, and waves either upstream or downstream, or both that appear to be generated at or associated with the shock. Table 1 lists the jump in B, the angle between the magnetic field and the shock normal and the Mach number of the shocks. The leading shock with the weak field jump is close to being a quasi-parallel shock with θ_{BN} close to 45°. The slightly stronger shock is quasi-perpendicular with a θ_{BN} of 76°.

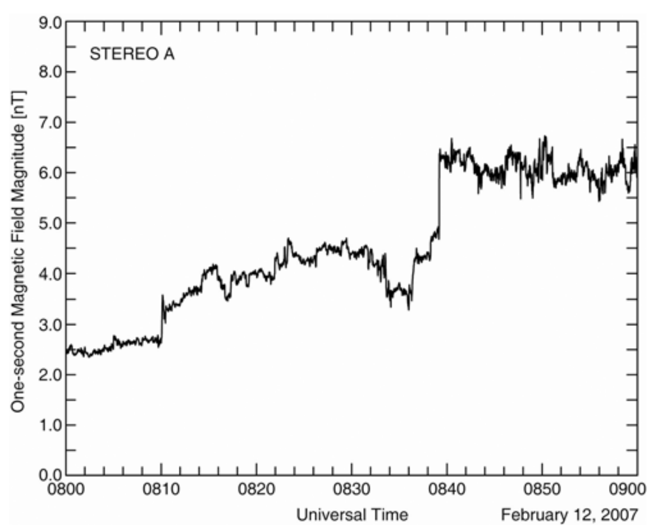

Figure 1. One-second measurements of the magnetic field strength from STEREO A on February 12, 2007, showing the magnetic field across two successive weak shocks.

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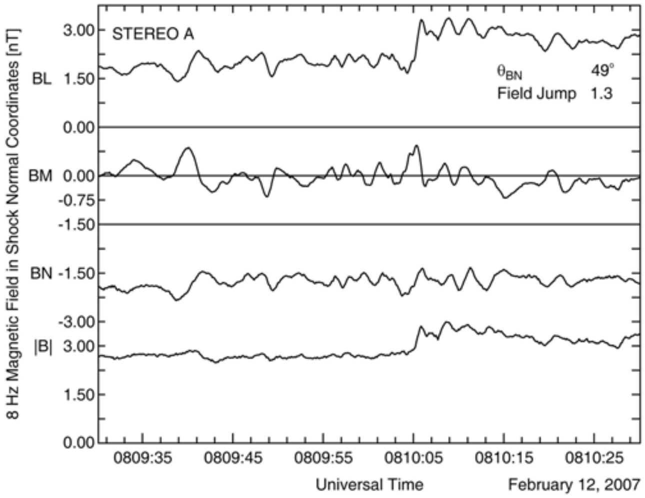

Figure 2. Eight-Hertz vector magnetic field data from STEREO A across the leading shock shown in Figure 1. Shock co-planarity coordinates are used based on average fields upstream and downstream of the shock. BL is the component in the shock plane parallel to the projection of the upstream magnetic field. BN is the field component along the normal direction, and BM in the component in the plane of the shock perpendicular to the projection of the upstream field on the shock. The L, M, N axes form a right-handed coordinate system.

[4] Figure 4 shows two successive shocks on another day. A third (following) jump has not yet steepened into a shock. When we look at the 8-Hz magnetic field components in shock normal coordinates across the first shock, we see in Figure 5 a weak but sharp jump, but very little significant wave activity. The field strength only increases 10%. The second shock shown in Figure 6 has a similar strength jump in the magnetic field, but this shock has significant wave activity upstream and downstream. We note that the leading shock here is more quasi-perpendicular than the trailing shock.

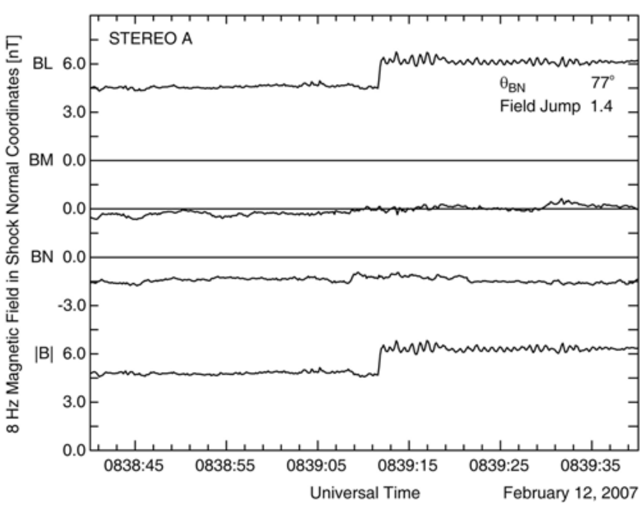

Figure 3. Eight-Hertz vector magnetic field data from STEREO A across the second shock in Figure 1. Comments of Figure 2 caption apply.

Table 1. Parameters of Overtaking Shocks

Spacecraft	Data	UT	Bdu/Bup	θ_{BN}	Mach
A	2/12/07	0810	1.3	49°	1.3
A	2/12/07	0839	1.4	77°	1.3
A	11/20/07	2340	1.1	70	1.1
A	11/20/07	2350	1.1	62	1.1

[5] We conclude from our examination of these two shock pairs that weak shocks do strengthen by coalescence. We note that thus far we have not observed stronger shocks coalescing in this manner, but we have found many pairs of weaker compressional waves in stream interaction regions, neither of which has yet steepened into a shock, that appear to have shock formation as their ultimate fate.

3. Shock Incubator Region

[6] As STEREO A and B slowly drift apart, Venus at 0.72 AU provides an upstream solar wind monitor for them every eighteen months. Thus far, there has been one conjunction each: on August 2, 2007, for STEREO B, and September 15 for STEREO A. We scanned the Venus Express magnetic records for a period of 30 days, centered on each of the conjunctions, and found no shocks at Venus Express, but we saw nine shocks at STEREO. These shocks are listed in Table 2 together with various shock parameters. These shocks are all relatively weak at 1 AU, ranging from 1.2 to 1.9 in fast magnetosonic Mach numbers. Hence, it is clear that these shocks are forming between the orbits of Venus and the Earth.

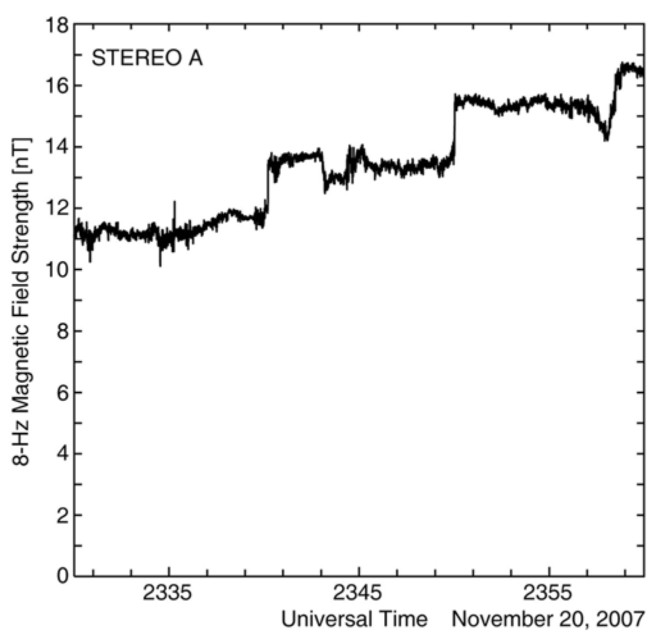

Figure 4. One-second magnetic field magnitude across two shocks on November 20, 2007. The third jump has not yet steepened into a shock.

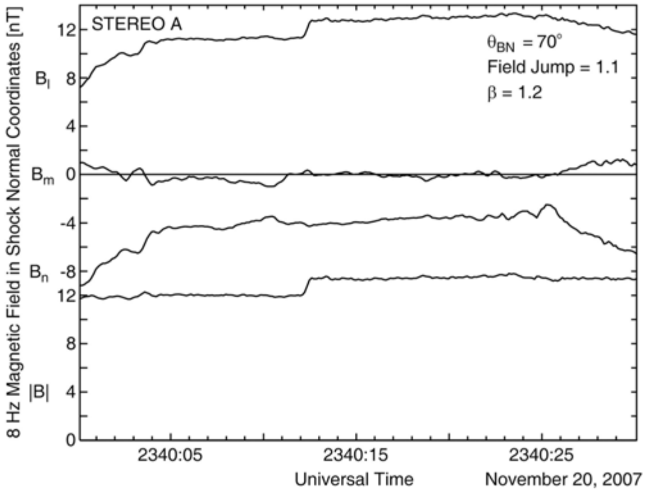

Figure 5. Eight-Hertz magnetic field components and total field across the leading shock in shock normal coordinates. Comments of Figure 2 caption apply.

4. Discussion and Conclusions

[7] The solar minimum conditions that STEREO has experienced since launch have been excellent for studying the more quiescent structures of the solar wind, such as stream interactions. These structures, beyond the orbit of Venus, are the breeding ground for the many SIR associated shocks we see at Earth. In our two-month study period, when the spacecraft were within 10° of radial alignment, we found no shocks at 0.72 AU, while we saw nine shocks at STEREO. When the stream interactions at 1 AU are examined carefully, we see evidence of the shock coalescence where weak shocks overtake other weak shocks, producing a stronger shock in their place. In the shock incubator region, we also see many compressional waves that have not yet steepened into shocks that appear to have shock formation as their ultimate destiny. This coalescence does not appear to be at work near strong shocks.

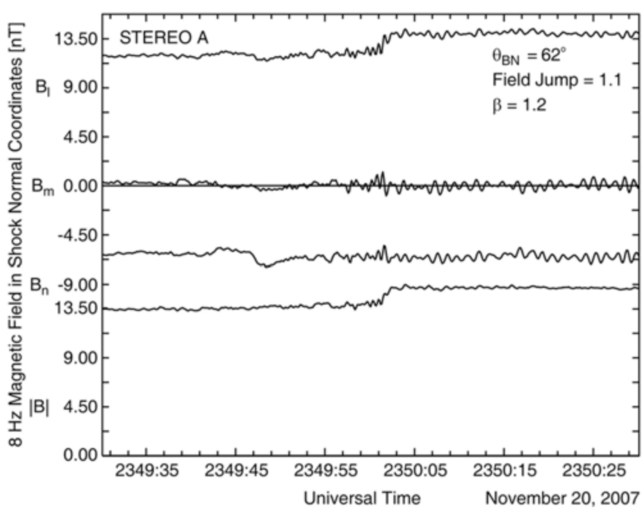

Figure 6. Eight-Hertz magnetic field components and total field across the following shock in shock normal coordinates. Comments of Figure 2 caption apply.

Table 2. Parameters of Shocks Observed During Venus Express Conjunctions

Spacecraft	Data	UT	Bdu/Bup	θ_{BN}	Mach
A	9/13/07	1754	1.2	81	1.2
A	9/15/07	0154	1.4	75	1.3
A	9/15/07	1535	1.3	70	1.2
A	9/23/07	1131	1.4	79	1.3
A	9/30/07	1109	1.6	77	1.4
B	7/20/07	0122	1.5	52	1.4
B	8/6/07	2208	1.6	75	1.5
B	8/10/07	1639	1.7	34	1.9
B	8/14/07	1631	1.3	57	1.2

[8] **Acknowledgment.** This work was supported by the National Aeronautics and Space Administration under grant NAS5-00133.

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