STEREO observations of upstream and downstream waves at low Mach number shocks

C. T. Russell,[1] L. K. Jian,[1] X. Blanco-Cano,[2] and J. G. Luhmann[3]

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[1] Early theories of upstream and downstream wave formation at laminar (low Mach number, low beta) shocks predicted that upstream waves would arise from phase-standing whistlers, propagating upstream along the shock normal. Downstream waves were attributed to nearly perpendicular shocks where waves had a different dispersion than the whistler mode, allowing them to stand downstream. Observations of low-Mach number shocks with STEREO reveal both upstream and downstream waves, but unlike the prediction of early theory, the downstream waves arise for a wide variety of shock conditions. These downstream waves appear to be compressional magnetosonic waves. **Citation:** Russell, C. T., L. K. Jian, X. Blanco-Cano, and J. G. Luhmann (2009), STEREO observations of upstream and downstream waves at low Mach number shocks, *Geophys. Res. Lett.*, *36*, L03106, doi:10.1029/2008GL036991.

1. Introduction

[2] Laminar collisionless shocks are low-Mach number shocks in a low-beta plasma where dispersion limits non-linear steepening, and a trailing or leading wave train is generated [*Biskamp*, 1973]. Low Mach number shocks have been extensively studied in the solar wind during the ISEE mission, where multiple spacecraft observations enabled accurate shock normals to be determined [*Russell et al.*, 1983a]. They were also studied at the Earth's bow shock on those infrequent occasions when the Mach number of the solar wind flow relative to the Earth reached low values [*Mellott*, 1985; *Farris et al.*, 1993]. These studies [*Russell et al.*, 1982a, 1983b] revealed two classes of upstream waves at these weak shocks: whistler-mode precursors which occur at low Mach numbers, and upstream turbulence, whose amplitude at Mach numbers greater than 1.5 is controlled by the angle of the field to the shock normal. The upstream whistler precursors are right-hand circularly polarized in the plasma frame, and quite monochromatic. The upstream turbulence is more linearly polarized and has a broadband turbulent spectrum. Downstream waves are also present at the low-Mach number shock but were not studied with the ISEE data, except for the overshoot phenomenon [*Russell and Greenstadt*, 1979; *Russell et al.*, 1982b]. The original hypothesis for the formation of downstream waves in laminar shocks was that the standing waves at the shock stood downstream when the shock became nearly perpendicular and the dispersive properties changed [*Biskamp*, 1973].

[3] The advantage of studying standing planetary shocks is that the shock is moving relatively slowly, and its normal is roughly determined by the expected geometry of a bow shock. The disadvantage is that the conditions that allow the Earth's bow shock to be laminar occur rarely, are restrictive in their parameter ranges when they do occur, and cause the location of the bow shock to move outward. The weakest bow shocks are very difficult to study with a single spacecraft, because, as they move backward and forward, the Mach number can change substantially, and the shock can disappear entirely until it reforms on an outward cycle [*Russell and Zhang*, 1992]. Recently, a single very low-Mach number shock observed at Venus with a downstream wave train was interpreted in terms of kinematic relaxation instead of dispersive dissipation [*Balikhin et al.*, 2008]. This new interpretation is attractive because downstream waves, as we will demonstrate below, occur much more often than just when the shock is perpendicular. Since no plasma data were available at the time of the Venus shock crossing, because of the moderately large possible offset ($\sim$1 nT) on Venus Express, and because of the sensitivity of low-Mach number shocks to back and forth motion as discussed

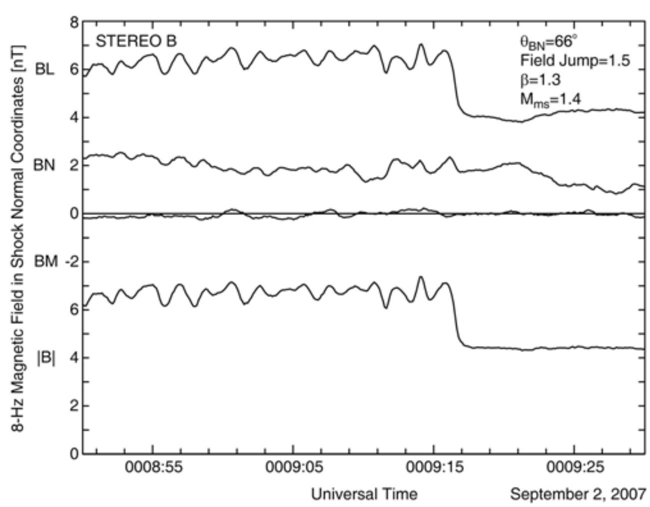

Figure 1. Eight-Hertz magnetic field measurements in shock normal coordinates for the September 2, 2007, shock on STEREO B. The BL component is in the shock plane in the direction parallel to the projection of the upstream magnetic field. The BN direction is along the shock normal, and BM is in the shock plane perpendicular to BL. The LMN coordinates form a right-handed system.

[1]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.
[2]Instituto Geofisica, Universidad Nacional Autonoma de México, Mexico D. F., Mexico.
[3]Space Science Laboratory, University of California, Berkeley, California, USA.

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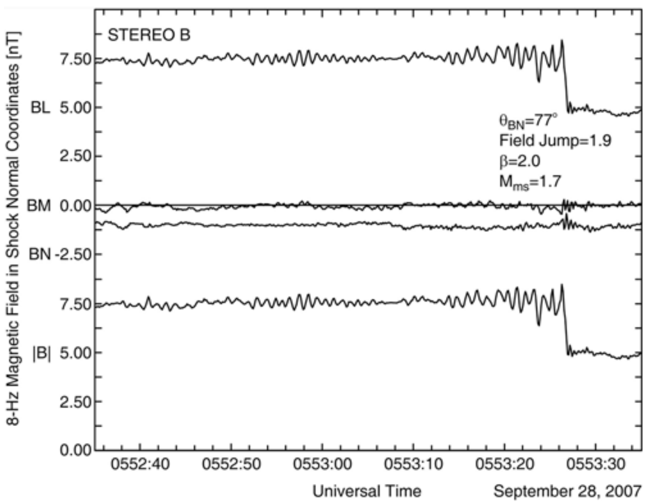

Figure 2. Eight-Hertz magnetic field in shock normal coordinates for the September 28, 2007, STEREO B shock. Comments for the caption of Figure 1 apply.

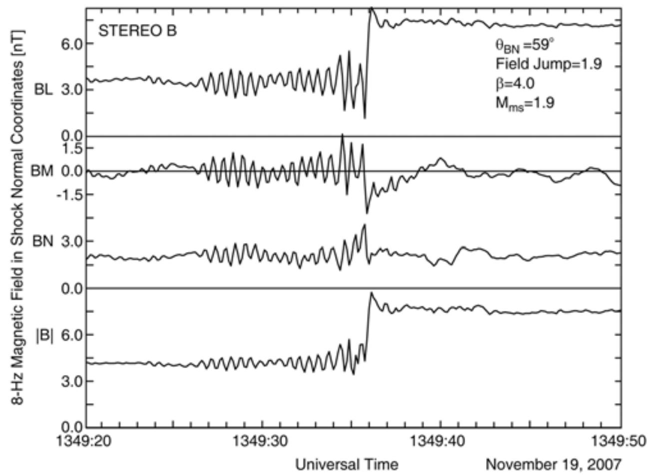

Figure 3. Eight-Hertz magnetic field in shock normal coordinates for the November 19, 2007, STEREO B shock. This is to be contrasted with Figure 2. Comments for the caption of Figure 1 apply.

above, we need to hold this conclusion, based on a single shock observation, in abeyance for further confirmation.

[4] In this paper, we examine the low-Mach number shocks observed by STEREO A and B in 2007, to determine the range of conditions under which downstream waves occur. We believe we have not observed the same shock conditions as occurred in the Venus Express example, but the results of our survey are of interest in that they reveal that downstream waves are not unusual for low Mach number interplanetary shocks.

[5] Low Mach number shocks occur frequently in interplanetary space at stream interactions where shocks begin to grow between Venus and Earth [*Russell et al.*, 2009]. The advantage of interplanetary observations is that the shock is moving moderately uniformly. The disadvantage is that the shock normal is not in an a priori known direction. A further disadvantage is that the shock passes the spacecraft quickly so that a fairly high cadence is needed to resolve the wave structure. Since the STEREO magnetometer generally operates at an 8 Hz sample rate, it can resolve a wide range of upstream precursors. In the data obtained in 2007, about 20% of the shocks were also captured in burst mode data at 32 Hz. In this paper, we examine a number of weak STEREO interplanetary shocks to determine if upstream and downstream waves are exclusive phenomena or whether they can occur simultaneously.

2. Upstream and Downstream Wave Occurrence

[6] As noted above, the original theory of laminar shock dissipation predicted upstream waves to occur at oblique shocks and downstream waves for perpendicular shocks. To compare the STEREO observations with expectations of laminar shock theory, we selected from nearly 60 shocks obtained during a year of STEREO operations in the solar wind. In this study, we present all the data in shock normal coordinates with N along the normal, L along the projection of the upstream field on the shock plane, and M in the shock plane perpendicular to L and N so that LMN forms a right-handed set. We calculate the shock normal coordinate system from average fields obtained upstream and downstream from the shock using the coplanarity assumption that the upstream field, the downstream field and the shock normal all lie in a plane. The Mach number is calculated from the field jump for the observed plasma conditions using the Rankine-Hugoniot conditions. The offsets of the magnetometer are known to 0.1nT using the procedure outlined by *Leinweber et al.* [2008].

[7] Figure 1 is a weak oblique shock with a shock normal angle, θ_{BN}, of 66°, and the waves are clearly only downstream. The waves are mainly compressional but have some transverse component. Because magnetic fields are divergenceless, the direction of minimum variance is the direction of propagation of plane waves. The waves' minimum variance direction, θ_{kn}, is 82° to the shock normal. Figure 2 shows a stronger shock with a θ_{BN} of 77°, also oblique and a principally downstream wave structure. These two examples show that downstream waves occur for θ_{BN} quite different than 90°. Figure 2 also shows a very weak precursor wave upstream. If we calculate the direction of the phase propagation of this upstream wave, we find that

Table 1. Shock Parameters and Upstream Wave Analysis Results

S/C	Date	Time	$\hat{n}$ (R, T, N)	θ_{BN}	$\hat{k}$ (LMN) [up]	Up θ_{kN}	Forward or Reverse	Mms	β
B	9/2/07	0009:17	(0.090, 0.160, 0.983)	66°	No precursor	–	R	1.4	1.3
B	9/28/07	0553:26	(0.792, 0.247, 0.558)	77°	(0.605, −0.356, 0.712)	40°	R	1.7	2.0
B	11/19/07	1349:35	(0.977, 0.139, 0.161)	59°	(0.556, 0.148, −0.818)	34°	F	1.9	4.0
A	1/14/07	1935:07	(0.989, 0.051, 0.137)	59°	(0.114, 0.037, −0.993)	7°	F	1.2	1.0[a]
A	8/25/07	2030:01	(0.719, 0.214, −0.661)	71°	(0.611, 0.350, −0.710)	41°	F	1.8	3.4
B	11/9/07	0010:08	(0.775, 0.165, 0.610)	64°	(0.389, 0.027, 0.921)	23°	F	2.0	2.4

[a]Assumed.

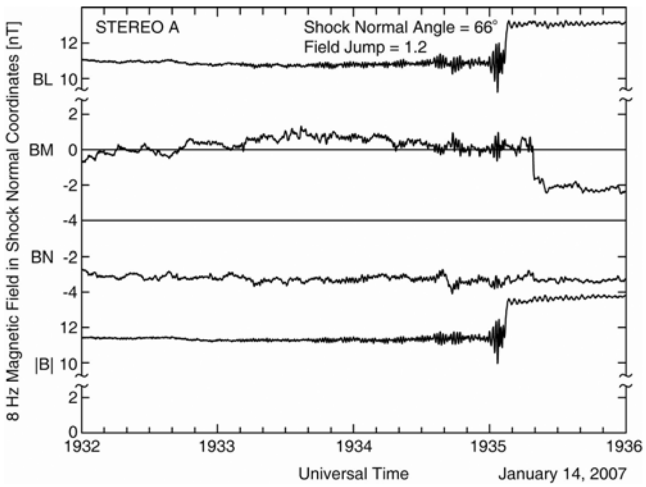

Figure 4. Eight-Hertz magnetic field in shock normal coordinates for the January 14, 2007, STEREO A shock. Comments for the caption of Figure 1 apply.

the wave is not propagating along the shock normal, but at an angle of 40° (See Table 1).

[8] We contrast Figure 2 with a more oblique shock with θ_{BN} of 59° in Figure 3. Here, the wave has switched to upstream only. In this example, the wave is much stronger, and the shock precursor's k-vector much easier to accurately determine. Here it is directed 34° to the shock normal. Figure 4 shows a STEREO B quasi-perpendicular shock with θ_{BN} near 66°. The precursor wave is traveling at 26° to the normal. The downstream waves here are propagating at 86° to the normal, and the waves are quite compressional. We do not have plasma data for this shock, but the strong magnetic field suggests that beta may be low.

[9] Figures 5 and 6 show another comparison pair obtained at STEREO A on August 25, 2007, and at STEREO B on November 9, 2007. They both have a small upstream precursor, but have major downstream wave structure, even though they are quasi-perpendicular shocks with shock normal angles of 71° and 64°. The precursor waves are again propagating at significant angles, 41° and 23°, to the normal direction.

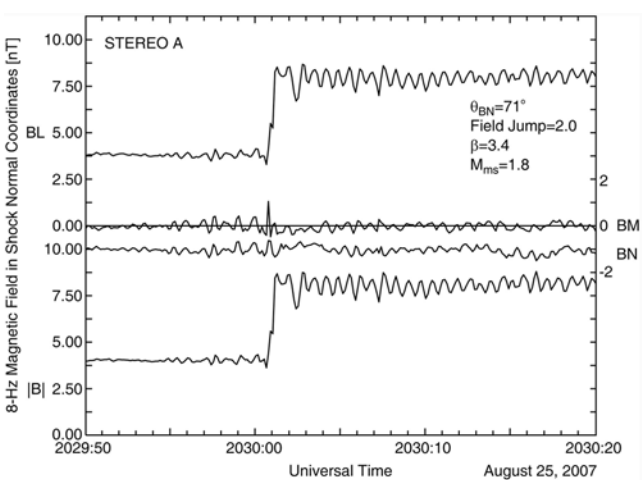

Figure 5. Eight-Hertz magnetic field in shock normal coordinates for the August 25, 2007, STEREO A shock. Comments for the caption of Figure 1 apply. This is to be contrasted with Figure 4.

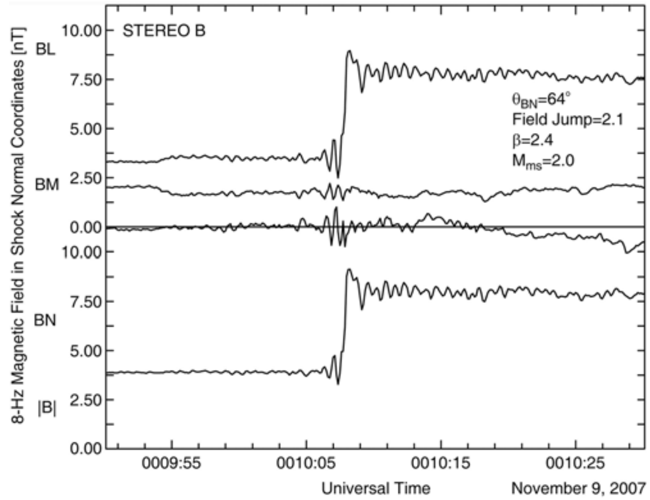

Figure 6. Eight-Hertz magnetic field in shock normal coordinates for the November 9, 2007, STEREO B shock. This is to be contrasted with Figure 6. Comments for the caption of Figure 1 apply.

[10] Downstream waves are observed in five of our shock examples. We have analyzed a portion of these waves and include their properties in Table 2. In Figures 1 and 2 are reverse shocks propagating toward the Sun, but being carried outward by the solar wind. Figures 4, 5, and 6 show forward shocks propagating away from the Sun. In each of these five examples, as can be seen in Figures 4–6, the regular downstream magnetic variation is small along the normal direction. The minimum variance analysis responds to the downstream wave and other non-wave changes in the field. Thus, the maximum eigen vector is not always determined by the wave. In these cases, Figures 2, 5, and 6, the waves are dominant and the maximum eigen vector is mainly aligned along the L-direction, in the shock plane along the projection of the magnetic field. The k-vectors are less well-determined, and are at a variable angle from N. Measured in the LN plane, this angle is 14° from N on September 2, 2007; 1° on September 28, 2007; 60° on January 14, 2007; 17° on August 24, 2007; and 0° on November 9, 2007. The fact that the waves are compressional suggests that they are magnetosonic, but until we obtain high-resolution plasma data, we cannot test this.

3. Discussion and Conclusions

[11] We have examined nearly 60 shocks in the interplanetary medium during the first year of operation of STEREO A and B outside the influence of the Earth. This is a very rich data set for the study of the physics of low Mach number shocks. In this paper, we examined six of these shocks to test our current ideas of upstream and downstream waves. These upstream waves propagate over a range of angles to the shock normal and occur over a broad range of plasma conditions. Such waves are a common occurrence, but do sometimes not appear.

[12] The downstream waves are compressional, and often the magnetic field perturbation is largest along the L-

Table 2. Downstream Wave Analysis Results

S/C	Date	Start and Stop Times	Eigen Values	Max Eigen Vector	θ_{iL}	θ_{kN}
B	9/2/07	0008:53–0009:14	(0.093, 0.056, 0.012)	(0.344, 0.064, 0.937)	70°	14°
B	9/28/07	0553:15–0553:25	(0.150, 0.017, 0.007)	(1.000, −0.010, 0.024)	0°	1°
A	1/14/07	1935:10–1939:19	(0.092, 0.033, 0.006)	(0.144, 0.889, 0.434)	82°	60°
A	8/25/07	2030:04–2030:15	(0.123, 0.031, 0.012)	(0.958, 0.217, 0.187)	17°	17°
B	11/9/07	0010:04–0010:18	(0.056, 0.050, 0.009)	(0.978, −0.116, −0.175)	12°	0°

direction along the projection of the upstream field on the shock surface. The direction of propagation of these waves is not as well determined as the more transverse upstream waves. We note that the only currently available plasma moments from STEREO are proton speed, density, and temperature. Velocity components and composition are not yet calculated.

[13] In summary, downstream compressional waves occur frequently for low Mach number interplanetary shocks. They occur over a range of θ_{BN} angles, and are not just a perpendicular shock phenomenon.

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X. Blanco-Cano, Instituto Geofísica, Universidad Nacional Autonoma de México, Mexico D. F. 04510, Mexico.

L. K. Jian and C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA. (ctrussel@igpp.ucla.edu)

J. G. Luhmann, Space Science Laboratory, University of California, Berkeley, CA 94720-7450, USA.