Study of Interplanetary Shocks Using Multi-Spacecraft Observations

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Abstract. We investigate the characteristics of interplanetary (IP) shock waves associated with a stream interaction region (SIR) observed during April 21-24, 2007 by STEREO-A/B, WIND and ACE spacecraft. During the years 2007-2008 STEREO-A observed 43 and STEREO-B crossed 41 shocks. As IP shocks propagate, they encounter solar wind with different characteristics (density, speed) and different orientations of the ambient magnetic field. Hence, it is expected that shock profiles will vary strongly through the space. We use magnetic field and plasma data to study shock structure, strength and orientation. In this example of a SIR we find that the characteristics of the shocks change dramatically from one region to another, the shock structure can be quasi-perpendicular as observed in one spacecraft and quasi-parallel when crossed at other point. Low frequency waves with different characteristics appear upstream and downstream of forward and reverse shocks. In this example the region upstream of the forward quasi-perpendicular shock observed by STEREO-A shows whistler mode waves, associated with the shock. However, STEREO-B observed the same shock but with a quasi-parallel structure, showing not only low frequency (∼0.1 Hz) waves very near to the shock but also at an extended foreshock region ahead of the shock front.

Keywords: Interplanetary shock waves.
PACS: 96.50

INTRODUCTION

During the years 2007-2008 the STEREO mission observed a large number of IP shocks driven principally by stream interactions. This is because the Sun is at its minimum of activity. In total STEREO-A observed 43 IP shocks and STEREO-B detected 41 shocks (level 3 shock list is available at *http://www-ssc.igpp.ucla.edu/forms/stereo/stereo_level_3.html*). Most of the shocks were quasi-perpendicular ($\Theta_{BN} \geq 45°$) with only 16 quasi-parallel ($\Theta_{BN} \leq 45°$) events. In some cases these shocks were associated with well developed SIRs at 1 AU. As the twin spacecraft were drifting apart, we can compare the structure of the same shock as it encounters differing magnetic geometry and plasma conditions. ACE and WIND give us another data point, or two if they are well separated. Understanding these variations is important in the context of shock acceleration models where waves and turbulence associated with IP shocks play a major role.

SHOCK CHARACTERISTICS

Figure 1a and 1b show plasma data from STEREO/PLASTIC [1], WIND/SWE [2], and ACE/SWEPAM [3]; as well as magnetic field data from STEREO/IMPACT [4], WIND/MFI [5], and ACE/MAG [6], for April 21-24, 2007 when a stream interaction region was observed. All the four spacecraft observed two IP shocks during this period of time, corresponding to the forward and reverse SIR shocks. On April 21 STEREO-A observed a well developed forward quasi-perpendicular (Θ_{BN}=77°) shock (Figure 2a). The sharp jump in the quasi-perpendicular shock is in contrast to the more gradual and fluctuating quasi-parallel (Θ_{BN}=40°) shock observed by STEREO-B (Figure 2b) on April 22, ∼11 hours later. WIND (Figure 2c) and ACE (Figure 2d) spacecraft observed a quasi-perpendicular and a quasi-parallel shock with values of Θ_{BN}=52° and Θ_{BN}=14°, respectively, around 5 hours later than STEREO-A, and ∼5 hours before STEREO-B. As shown in Figure 3, STEREO-A was closer to the Sun so that it is possible that both spacecraft observed the same shock front whose characteristics change with longitude due to the different solar wind conditions that the disturbance finds as it travels through IP space. The Mach number for the forward shock varied from 1.32 to 1.81. On April 23 STEREO-A observed a well developed reverse quasi-perpendicular (Θ_{BN}=73°) shock (Figure 2e), while STEREO-B observed a quasi-parallel (Θ_{BN}=34°) shock ∼6 hours later (Figure 2f). WIND (Figure 2g) also detected a quasi-parallel reverse shock (Θ_{BN}=12°) and ACE (Figure 2h) observed a quasi-perpendicular (Θ_{BN}=77°) reverse shock ∼4 hours before STEREO-B. The Mach numbers for the

CP1216, *Twelfth International Solar Wind Conference,*
edited by M. Maksimovic, K. Issautier, N. Meyer-Vernet, M. Moncuquet, and F. Pantellini

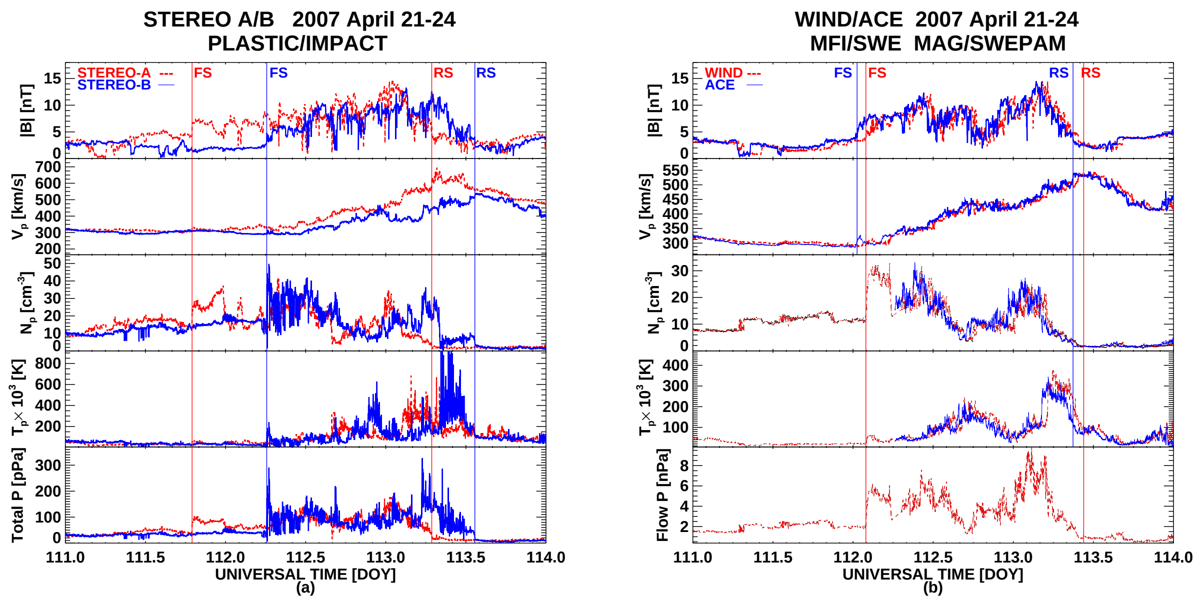

FIGURE 1. Magnetic field intensity (|B|), proton speed (V_p), proton density (N_p), proton temperature (T_p), total pressure (sum of magnetic pressure and perpendicular plasma thermal pressure), and flow pressure (plasma thermal pressure) of forward (FS) and reverse (RS) IP shocks observed by (a) STEREO and (b) WIND/ACE spacecraft on April 21-24, 2007. STEREO magnetic field and plasma data are plotted at a resolution of 1 minute each. Magnetic field and plasma data are plotted at a resolution of 1 minute and 64 seconds for WIND and ACE spacecraft, respectively.

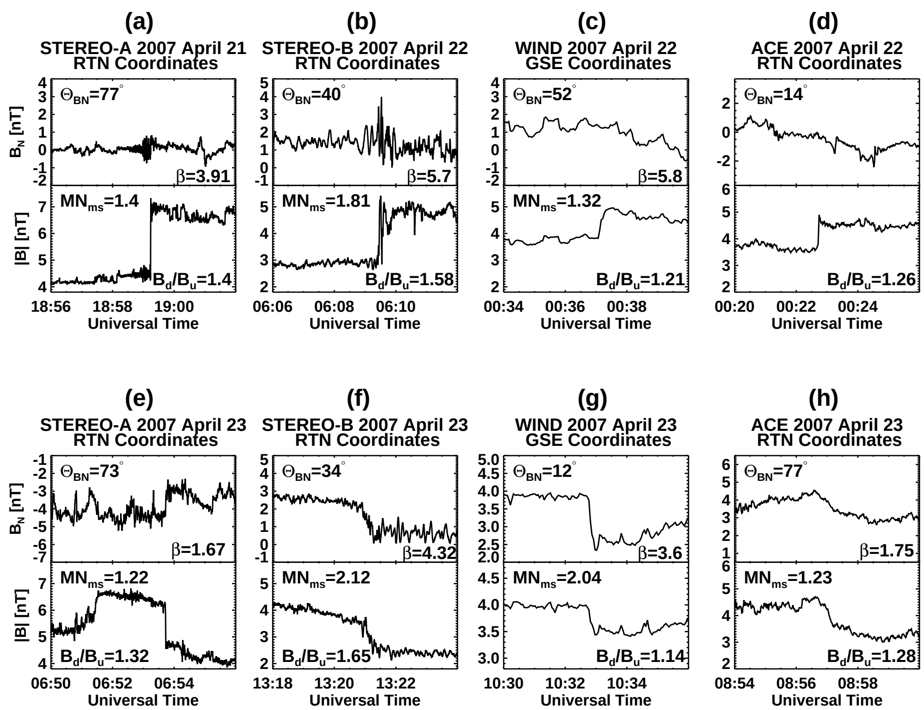

FIGURE 2. Forward and reverse shocks. Time intervals of STEREO, WIND and ACE magnetic field data at 8 Hz, 3 s, and 1 s time resolution, respectively. The angle (Θ_{BN}) between the IP magnetic field and the shock normal is derived from shock coplanarity theorem. Magnetosonic Mach number (MN_{ms}) is obtained from Rankine-Hugoniot equations. B_d/B_u is the ratio of downstream magnetic field intensity to upstream magnetic field intensity. All profiles are plotted in RTN coordinates, except for WIND, which are plotted in GSE coordinates.

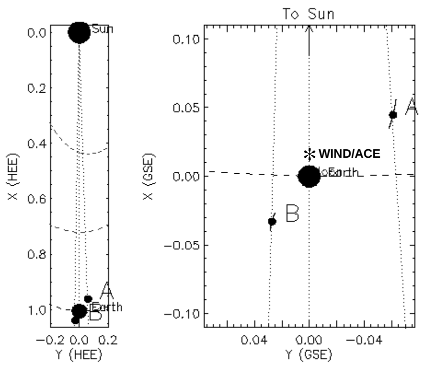

FIGURE 3. Location of the spacecraft on April 21-24, 2007.

reverse shock varied from 1.22 to 2.12. The largest differences between shock characteristics were observed at STEREO-B where both shocks (forward and reverse) were quasi-parallel and with larger Mach number.

By checking SECCHI/STEREO-A/B [7] images on April 16, 2007, corresponding to the day when the solar wind stream that drives these shocks should have left the Sun, we identified a large coronal hole at mid-latitudes suggesting that it could be the source of the stream that generates these shocks. Of particular interest during the present solar minimum is the fact that stream interactions have caused a considerable number of weak shocks at 1 AU.

The characteristics of shock profiles and their associated upstream waves depend strongly on Θ_{BN}, the Mach number and the plasma beta. The IP shocks in Figures 1a and 1b, show that in spite of the fact that four spacecraft observed the same shock fronts associated with a SIR, the shocks characteristics were different. STEREO-A and WIND observed a quasi-perpendicular forward shock, while STEREO-B and ACE crossed a quasi-parallel structure. As for the reverse shock fronts, STEREO-A and ACE observed a quasi-perpendicular shocks, while STEREO-B and WIND found a quasi-parallel structure.

WAVES UPSTREAM

Previous studies have shown that low Mach number shocks are accompanied by upstream whistler precursors, while at Mach numbers greater than 1.5 the wave spectra becomes more turbulent with characteristics that depend on Θ_{BN} [8]. Figure 4 shows wave properties of the upstream region of the forward quasi-perpendicular shock observed by STEREO-A on April 21, 2007 (see

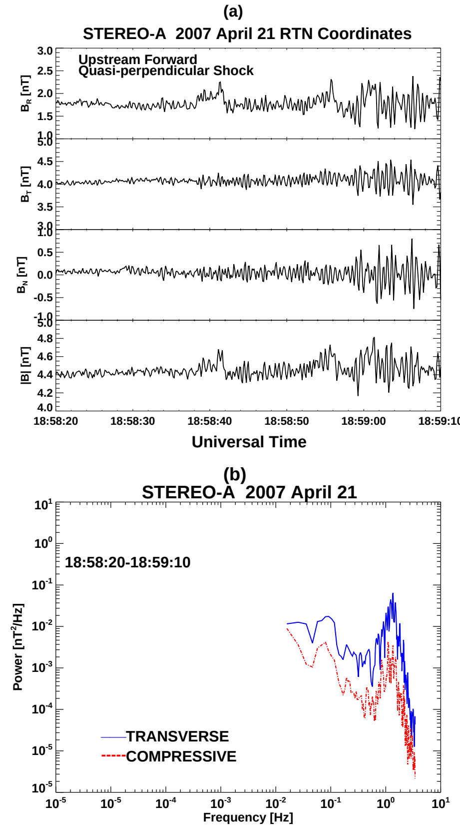

FIGURE 4. (a) magnetic field time series, and (b) power spectrum of the upstream region of a forward quasi-perpendicular shock observed by STEREO-A on April 21, 2007 (see Figure 2a). The compressive power is defined from the total power P_{tot} which is the result of applying FFT to the total magnetic field $|\mathbf{B_0}|$, while the transversal power is defined as $|P_r+P_t+P_n-P_{tot}|$, where P_r, P_t, P_n, are the powers of B_r, B_t, and B_n, respectively.

Figure 2a). Figure 4a shows an example of a typical signature of whistler precursors. We can notice that these waves have larger amplitude as we approach to the shock, which occurs at 18:59:15 UT with $\Theta_{BN} \sim 77^\circ$. These waves appear very near to the shock, lasting $\sim$1 minute, which indicates an extension ahead of the shock of $\sim 1.68\times10^4$ km. These waves have frequencies around 1 Hz as shown in the power spectra in Figure 4b, and propagate at a small angle (Θ_{B_0k}=14°) to the ambient field. These waves are circularly right-handed polarized. In contrast, Figure 5 shows an example of the low frequency (f$\sim$0.08 Hz) waves observed upstream of the quasi-parallel shock observed by STEREO-B, with Θ_{BN}=40° and MN_{ms}=1.81. The interval where waves are observed lasts $\sim$11 min, which correspond to an extended foreshock region around 2.04×10^5 km. These waves are circularly and elliptically polarized with angles of propagation Θ_{B_0k} up to $\sim$40° and Θ_{nk}=43° with respect to

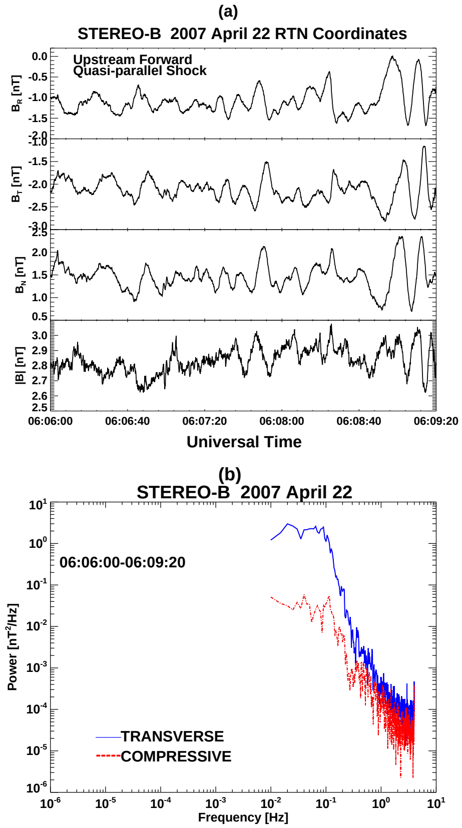

FIGURE 5. (a) magnetic field time series, and (b) power spectrum of the upstream region of a forward quasi-parallel shock observed by STEREO-B (see Figure 2b).

the shock normal. Their characteristics and the fact that this type of waves have not been observed upstream of quasi-perpendicular shocks, suggests that these fluctuations are generated locally by reflected or leaked ion beams. More work is needed to identify the beams generating the waves and the plasma conditions required for the waves to grow.

SUMMARY

The example presented in this work shows that IP shocks are complex structures surrounded by regions where different plasma characteristics exist. STEREO dual observations combined with WIND and ACE spacecraft, show that the characteristics of the shocks can change dramatically from one region to another (see e.g., Mason et al., 2009 and references therein). Shocks fronts can be quasi-parallel at one location, and quasi-perpendicular at other. Low frequency waves with different characteristics appear upstream and downstream of forward and reverse shocks. In this example the region upstream of the forward quasi-perpendicular shock observed by STEREO-A shows whistler mode waves generated at the shock. However, STEREO-B observed the same shock but with a quasi-parallel structure, showing not only low frequency waves very near to the shock but also at an extended foreshock region ahead of it ($\sim 2.04 \times 10^5$ km), lasting around 11 min. Thus, the region of the solar wind perturbed by the shock front can vary with longitude depending on the shock geometry. It is expected that in some SIRs mirror mode waves (and storms) may be present (see paper by Enriquez-Rivera et al. in this volume). Future work involves the study of turbulence and wave mode superposition in the SIR compression region. Understanding the variation of wave signatures in regions associated with SIR shocks as well as the variable shock properties is of great importance to test models of shock acceleration and the production of energetic ions in SIRs.

ACKNOWLEDGMENTS

We thank A. B. Galvin (PLASTIC), K. W. Ogilvie (SWE), D. J. McComas (SWEPAM), R. P. Lepping (MFI), and C. W. Smith (MAG) for the plasma and magnetic field data used in this work.
The work by E. Aguilar-Rodriguez at UNAM was supported by DGAPA-PAPIIT grant IN110309-2.
X. Blanco-Cano thanks CONACyT project, grant 81159.

REFERENCES

1. A. B. Galvin, et al., *The Plasma and Suprathermal Ion Composition (PLASTIC) Investigation on the STEREO Observatories*, Space Sci. Rev., 136, 437-486, 2008.
2. K. W. Ogilvie, et al., *SWE, a comprehensive plasma instrument for the WIND spacecraft*, Space Sci. Rev., 71, 55-77, 1995.
3. D. J. McComas, et al., *Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer*, Space Sci. Rev., 86, 563-612, 1998.
4. M. H. Acuña, et al., *The STEREO/IMPACT Magnetic Field Experiment*, Space Sci. Rev., 136, 203-226, 2008.
5. R. P. Lepping, et al., *The WIND Magnetic Field Investigation*, Space Sci. Rev., 71, 207-229, 1995.
6. C. W. Smith, et al., *The ACE Magnetic Fields Experiment*, Space Sci. Rev., 86, 613-632, 1998.
7. R. A. Howard, et al., *Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)*, Space Sci. Rev., 136, 67-115, 2008.
8. C. T. Russell, E. J. Smith, B. T. Tsurutani, J. T. Gosling, S. J. Bame, *Multispacecraft observations of interplanetary shocks: Characteristics of the upstream ULF turbulence*, in JPL Solar Wind Five, 1983, pp. 385–400.
9. G. M. Mason, et al., *In situ Observations of CIRs on STEREO, Wind, and ACE During 2007 - 2008*, Sol. Phys., 256, Issue 1-2, pp. 393-408, 2009.