Multi-point observation of the shock front longitudinal extent in the inner heliosphere

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Abstract

The two Helios probes traveled at variable longitudinal and radial separations through the inner heliosphere. They collected most valuable high resolution plasma data for an entire solar cycle. The mission is still so successful that no other missions will collect the same kind of data in the next 20 years. One of the subjects studied after the success of the Helios mission was the identification of more than 390 shock waves driven by Interplanetary Coronal Mass Ejections (ICMEs). Combining the data from both probes, we make a statistical study for the extension of shock waves in the interplanetary medium. For longitudinal separations of 90 degrees we found a cutoff value at this angular separation. A shock has 50% of chance to be observed by both probes and the same probability for not being observed by two spacecrafts at the same time, when the angle between them is around 90 degrees. We describe how with decreasing separation the chance for shocks to be observed by both probes grows. Including plasma data from the ISEE-3 and IMP-8 spacecrafts, improves our statistical evaluation substantially.

Introduction

Interplanetary shock waves are the strongest abrupt perturbation in the solar wind, playing an important role in the solar-terrestrial environment variability. They are large-scale phenomena resultant of the propagation of interplanetary structures, such as ICMEs - the interplanetary counterparts of the coronal mass ejections (CMEs)(see terminology discussion by Schwenn (1996), Burlaga (2001) and Russell (2001)). The reason why they are formed is the fact that the relative speed between a fast stream (the ICME, in this case) and the background solar wind is often greater than the characteristic speed of the medium-magnetosonic speed. In the inner heliosphere - inside 1 AU - shocks driven by ICMEs are well formed, and the ICME-shock association has been observed since the first images from Solwind coronagraph were available (Sheeley et al., 1985). Sheeley et al. (1985) were the first to confirm that fast ICMEs were related to the shock formation.

The purpose of this work is to study the shock extension in the inner heliosphere using Helios, IMP-8, and ISEE-3 observations for the entire solar cycle 21.

Method

Helios was a mission composed by two twin probes, Helios 1 (H1) and Helios 2 (H2), that operated at the same time from 1976 until the beginning of 1981 (Porsche, 1984). Due to the long life of H1 (1974-1986), it has become possible to collect one of the most complet sets of plasma data over the time span of a full solar cycle for studying the solar wind evolution and variation into the inner heliosphere (Schwenn and Rosenbauer, 1984). Among the total set of shock waves detected by the instruments onboard Helios, 395 were classified as those driven by ICMEs. Corotating Interaction Regions (CIRs) were not included in the present work since they are normally related to shocks at distances further than 1AU (Hundhausen and Gosling (1976), Smith and Wolfe (1976)).

Each of the shocks from the full set of events was analyzed separately. Solar wind and magnetic field data from three different positions (H1 and H2, and ISEE-3 or IMP-8) contributed to the comparison of the shock signatures in these reference points. This provided the opportunity to estimate the total angular distance in longitude which one could expect a shock to expand to.

By using the list of shock/ICME events studied by Sheeley et al. (1985), we had the possible flare locations associated to the limb CMEs when H1 was located close to +-90 degrees from the Sun-Earth line. This enabled to correlate the shocks observed by H1 with the ones observed at Earth by IMP-8 or ISEE-3, once the flare location was giving further information about the possible direction the shock wave was being driven.

Among the large set of events, there were periods without observations from the solar wind and/or magnetic field instruments onboard the three missions. Sometimes gaps filled the period when the shock was expected to arrive. These cases were not included in the statistical analysis carried out in this study. Only safe events, with visible signatures of shocks, made part of the considered sample. However, for some of these cases with gaps, we could see a level enhancement in all solar wind parameters and magnetic field strength before and after the gap. For those cases, we saw that there was a shock, even though we could not say exactly its time of occurrence.

Another difficulty was to determine the periods when we expected IMP-8 to observe the shock arriving at Earth. The periods when IMP-8 was in the solar wind were not many, but contributed to improving the estimate, until ISEE-3 appeared in the scenario at the second half of the year 1978 with an orbit around point L1, constantly in the solar wind. Another aspect that has influenced a lot in our sample is the fact that H2 did not operate during the full solar cycle like H1 did. For many years we just had a constellation (a pair of probes) as an input to our statistical analysis.

The inspection is basically observational, based in the comparison among the different points of references and their observations. Figure 1 is one example of a strong shock observed by Helios 1 at 0.952 AU driven by a magnetic cloud in the interplanetary medium. As it is shown in Figure 2, the same shock was seen at H2 at 0.978 AU, however, the signatures of the “ejecta” are not visible on the solar wind and magnetic field parameters.

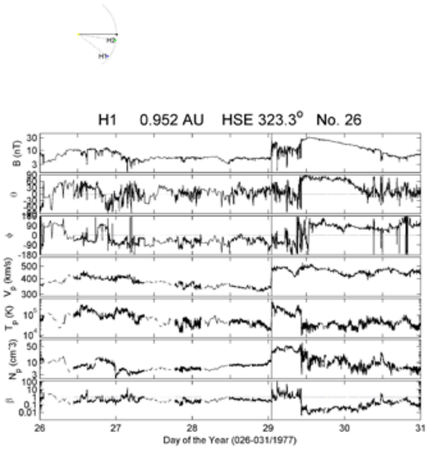

FIGURE 1: H1 magnetic field and plasma data for the shock detected on DOY 29/1977, at 01:03 UT. From top to bottom, one can see the magnetic field strength and angular components, followed by the solar wind proton speed, density, temperature, and the plasma beta. A magnetic cloud drives the shock, observed at 0.952 AU and 37 degrees away from Earth. At the top of the plot the position of the two probes H1 and H2 is shown, as well as the radial distance and longitude (in the counterclockwise direction in relation to the Sun-Earth line) of H1. Earth is schematically represented on the upper plot, as well as the Sun and H1 and H2 positions at the period of the shock. The Sun is the central point of the circumference sector from where the location lines of H1 and H2 for the period of the shock originate. The thicker solid line connects the center (Sun) to Earth.

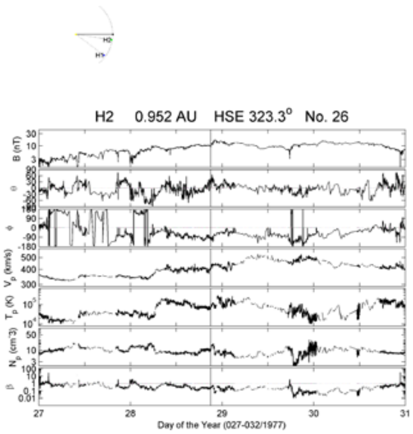

FIGURE 2: H2 observation of a shock wave on DOY 28/1977, at 21:07 UT. From top to bottom, one can see the magnetic field strength and angular components, followed by the solar wind proton speed, density, temperature, and the plasma beta. Radial and longitudinal distances of H2 are represented on the top.

The variation in B is very smooth and plasma β is going down after almost one day. Counting from the day of the shock, we may conclude that the probe was crossing only the shock wave and not the ICME structure itself. Near Earth, IMP-8 was the only spacecraft operating during this time (Figure 3). In this day, IMP-8 was outside the magnetospheric cavity, and the solar wind parameter profiles observed by IMP-8 were similar to the ones seen by H2. This was already expected since H2 and IMP-8 were separated by only 9 degrees. At the end of DOY 29/1977, the shock was detected by H2, and some hours later, by IMP-8.

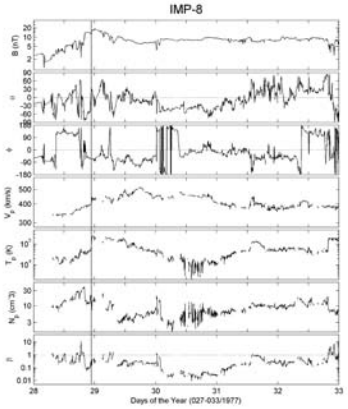

FIGURE 3: Interplanetary shock observed on DOY 28/1977 by IMP-8. This is the same shock previously observed by H2 and later on by H1. From top to bottom, one can see the profiles of the magnetic field strength and angular components, the solar wind protons speed, temperature, density, and plasma beta. IMP-8 was in the solar wind near Earth during the period of observation of this shock.

Based on the observations at the considered points we proceeded to estimate the shock extension in the interplanetary medium. We separated the three points of observation in three constellations of two spacecrafts each: H1 and H2, H1 and IMP-8/ISEE-3, and H2 and IMP-8/ISEE-3. From Figure 1 and 2 we associated the shock occurrence on H1 with the one at H2, which means that we considered this shock as being the same in each probe. Based on this association we say that the minimum longitudinal angular distance reached by the shock was the separation between H1 and H2 - in this case the shock extended at least to 28 degrees. When IMP-8 is included in the statistical analysis, a larger angle is considered: H1 and the Sun-Earth line are about 37 degrees of longitude away from each other. Again the minimum distance in longitude the shock reached was the one separating IMP-8 and H1, since the shock was crossed by these two spacecrafts when traveling in the interplanetary medium outwardly from the Sun. The angular separation between H2 and IMP-8 makes also part of the estimate once we are considering the three constellations independently.

We wanted to be sure we were seeing the same shock rather than to increase the number of cases studied without certainty. For this reason the rate of shocks does not correspond to the total number of shocks registered during the mission. The histograms showed in the next figures are a result of two different classes: shocks observed by a pair of probes (first panel), and shocks observed by a single probe (lower panel).

Since our results depend on the orbit of the probes, that probably did not observe all the shocks for the period and might have crossed the shocks in only one part, we might expect that there are larger angles than the ones we found. This guides us to the estimate of the margin of error.

Results

For each case the angular separation between a pair of spacecrafts represented the minimum separation we could expect a shock to extend into the interplanetary medium. As we separated the observations according to the three different constellations, three different estimates were obtained for the whole period of observation. From the group H1 and H2, smaller angles separated the two probes for most of the time of operation, so our estimate was limited to the angles they formed during their orbits. From H1 and H2 observations we could say primarily which shocks were observed in both spacecrafts, then look for other observations at Earth - first with IMP-8 and then with ISEE-3.

When near Earth observations by IMP-8/ISEE-3 were included on the estimate, larger angles started to appear and new shock extensions were revealed. The full longitudinal range of the inner heliosphere was covered by the new points included on the observations and a new scenario for the shocks extension estimate took place. Figure 4 shows the rate of shocks for each longitudinal separation considered. In that figure, the values vary from 10 to 170 degrees, and each column centered in a given ϕ represents the sum of all events in the interval I ($\phi \le I < \phi + 10$). This means that the number of cases centered in 20 degrees is a result of the number of cases in our sample where the angles were bigger than or equal to 20 and smaller than 30 degrees, and consecutively for the other angles in the x-axis.

As it is shown in Figure 4, there are bars that are in the right side up and others that are upside down for both the plots. The former ones correspond to those events where one of the constellations (two different points in the space) had seen the same shock. So from the different constellations separated by colors - H1 and H2 (black); H1 and IMP-8 (gray); and H2 and IMP-8 (white) -, we have the total number of cases in each angular separation considered from the set of shocks under study. And the later ones represent those shock waves observed by only one of the three points of reference. As it is shown in Figure 4, increasing the angular distance between two different observational points diminishes the number of events observed by each of the constellations.

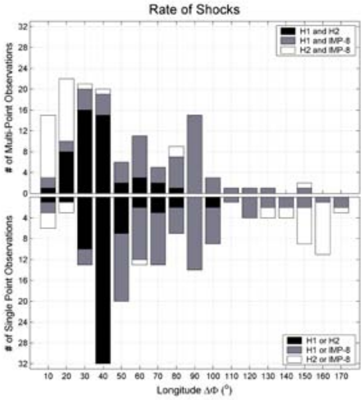

FIGURE 4: Number of shock waves observed from 1974 to 1985 by a pair of spacecrafts/probes (upper panel), or only by one of the spacecrafts (lower panel) as a function of the longitudinal separation ($\Delta\phi$) between the probes. The constellations are divided in three groups according to each pair of probes: Helios 1 and 2 (black), Helios 1 and IMP-8/ISEE-3 (gray), and Helios 2 and IMP-8/ISEE-3 (white).

In percentage, the distribution of our sample shows a clear trend that is illustrated in Figure 5. As we go to bigger angular separations, the percentage of shocks seen by both spacecrafts decreases, following a quasi-exponential decrease. Even though we have some special cases with large angles, like those events at 120, 130, and 150 degrees, we need to investigate them in details in order to certify that they really correspond to the same event seen in different points. According to the percentage we found in Figure 5, at $\Delta\phi = 90^o$ one has 50% of chance of seeing a shock or not seeing the same shock in two different points of observation.

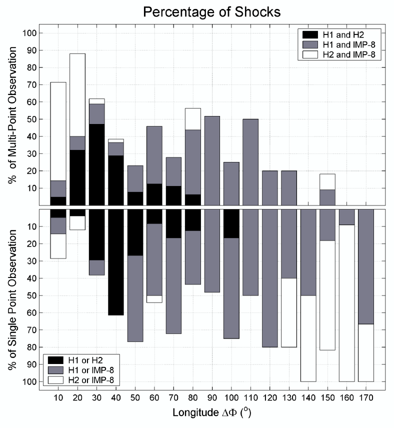

FIGURE 5: Percentage of safe events seen by multi-points (upper panel) and by single point (lower panel). Different constellations are separated by different colors: H1 and H2 (black), H1 and IMP-8/ISEE-3 (grey), and H2 and IMP-8/ISEE-3 (white).

The critical interval for the percentage of shocks (Figure 5) was determined by using the test of proportions analysis (for details, see Kalbfleisch (1979)). Figure 5 shows the error bars that represent a 95% confidence intervals for each angular separation. The estimated value is more accurate as we have a larger number of cases from the sample, like it is shown in Figure 5. A critical value at $\Delta\phi = 110$ is found as we have just two cases inside this angular distance.

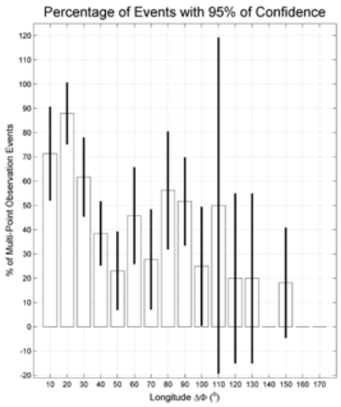

FIGURE 6: This is the same plot as shown before in the percentage of shocks (upper panel of Figure 5). The error margin for the percentage of shock observed by multi-points into each longitudinal separation as seen by Helios-1,2 and IMP-8/ISEE-3. As one goes further in degrees, the uncertainty for observing a shock in the angular separation ($\Delta\phi$) increases. Observe that in $\Delta\phi = 110$ the biggest error for our estimate is found. That is because only two events (Figure 4) were registered for that angle: one was detected by a pair of probes and the other by a single probe.

Conclusions

We have studied shock angular extension in the inner heliosphere using observations from H1, H2, and IMP-8/ISEE-3 spacecrafts. By using a pair of these probes each time, we found that shock extension decreases as the probes angular separation increases. When a CME is observed at the solar limb, for example, there is 50% of probability of seeing the shock driven by the ICME at Earth. Further investigation is needed to evaluate those cases with large $\Delta\phi \geq 110$ separation.

Acknowledgments

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