Five-spacecraft observations of interplanetary shock waves approaching solar maximum

J. A. GONZALEZ-ESPARZA[1].
[1]*Instituto de Geofisica, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Mexico DF 04510*

Abstract: We combined solar wind observations from six different spacecraft: Helios 1 and Helios 2 (from 0.3 to 1 AU), ISEE 3 and IMP 8 (at about 1 AU), Voyager 1 and Voyager 2 (from 1.2 to 2.5 AU), to study the structure of the solar wind streams and the propagation of interplanetary shocks approaching solar maximum (cycle 21). Comparing the simultaneos in-situ observations at five different locations is possible to illuminate some aspects of these events such as their logitudinal extent, radial evolution, and local structure.

Introduction

Numerical simulations of the solar wind dynamics in 2 and 3 dimensions show that Corotating Interaction Regions (CIRs), Transient Forward Shocks (TFSs) and ejecta, suffer important longitudinal and latitudinal deformations as they propagate through a structured ambient solar wind [3, 10, 9]. Under ideal circumstances a "cluster" of several spacecraft located at convenient positions could provide us with an extensive in-situ data set to study the global evolution of these large-scale perturbations. However, the data available to date limit most studies of these perturbations to single-spacecraft measurements. To address this problem, there have been several studies using observations from two different sources from which we know for example, that TFSs and ejecta decelerate as they propagate outward in the heliosphere and the front of a TFS can have an in-ecliptic longitudinal extension of about 100°, whereas ejecta have smaller extensions of about 60° (see e.g., [7] and references therein). The access to worldwide databases allows us to perform retrospective studies combining measurements from several spacecraft. In this study we compare simultaneous in-ecliptic observations from five spacecraft: Helios 1 (H1), Helios 2 (H2), IMP-8 (IMP), Voyager 1 (V1) and Voyager 2 (V2) during four Carrington rotations in the ascending phase of solar cycle 21, to discuss some characteristics of the structure of solar wind streams and the propagation of TFSs.

2. Data Analysis

The interval of study begins on November 1977 and ends on March 1978 (Carrington's rotations 1661–1665). We obtained trajectory files and hourly-averaged solar wind plasma and magnetic field data from the five spacecraft using NSSDC's COHO Web (http://nssdc.gsfc.nasa.gov/cohoweb/cw.html) and OMNI Web (http://nssdc.gsfc.nasa.gov/omni/). Figure 1 shows the five spacecraft trajectories in a frame of reference where the Sun-Earth line is fixed. Keep in mind that this reference system corotates with the Earth with an angular speed of about 360°/365 days $\sim$ 0.99° per day. In this frame the near Earth spacecraft (which is most often IMP 8 in the OMNI data set) was always located at 1 AU along the Sun-Earth line, while the other four spacecraft were continuously changing positions. H1 and H2 were moving in the inner heliosphere (at distances of 0.3 to 1.0 AU from the Sun) separated by about 30 degrees with respect to each other; whereas V1 and V2 were on route to Jupiter (traveling from 1.2 to 2.5 AU from the

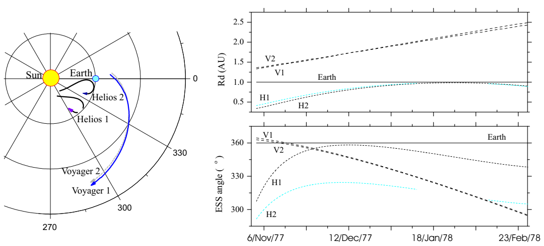

FIGURE 1

Figure 1: Trajectories of the five spacecarft from November 1977 to March 1978 as observed in a frame of reference where the Sun–Earth line is fixed.

Sun). In this study the angular separation between any of the five spacecraft was always less than 60° in longitude.

Shock identifications

With the data obtained from the COHO and OMNI Web we produced a series of 27-day plots of solar wind bulk speed (V_r), proton density (N_p), proton temperature (Tp) and the Interplanetary Magnetic Field (IMF) magnitude ($|B|$) for each spacecraft. Following the same criteria described by [6] we visually inspected these 27-day plots, looking for the characteristic profiles of TFSs and CIRs. After finding suitable candidates for transient shocks and CIR-associated shocks, we corroborated the shock identifications by plotting each shock in detail and checking it against the H1-H2 shock list by [11], the IMP shock list by [1] and the V1-V2 studies by [4], [2] and [8]. As reported previously [5], we identified 12 compressive large-scale events in this four month interval: 7 TFSs and 5 CIRs.

Figure 2 shows plots of radial solar wind speed, V_r, measured by the five spacecraft from November 1977 to March 1978. We recognize similar patterns in V_r in the five plots, indicating that the stream pattern was corotating with the Sun in a stable way within the longitude range covered by the five spacecraft. This similarity helps us identify the same shock event in the five data sets. Note the attenuation of bulk speeds with heliocentric distance. The differences in speed between slow and fast winds are greater in H1 and H2 observations than in V1 and V2 observations.

Figures 3 shows plots of proton density scaled by the square of the heliocentric distance ($N_p \times R^2$) versus time Unlike the plots of bulk speeds in Figure 2, we cannot easily recognize the same level of correspondence between the observations of N_p, T_p and $|B|$ made by the five spacecraft in Figures 3-5, as was the case with the velocity data. The plots of V_r are very similar for both H2 and IMP-8 (Figure 2), but the observations of N_p (Figure 3), show different structures detected by the various spacecraft. These types of local structures or inhomogeneities in N_p, were detected, in each case, by only one spacecraft, implying that they have small longitudinal extensions and might be time dependent. These inhomogeneities appear in regions which are not associated with shocks ('quiet regions') and they are not compressive events since the changes in N_p, T_p and $|B|$ are uncorrelated.

Summary

We studied an interval of four months during the ascending phase of solar cycle 21 combining simultaneous observations of five different spacecraft. These multi-spacecraft observations reveal the complex dynamics and evolution of solar wind perturbations that cannot be inferred using single-spacecraft or two-spacecraft measurements.

The main results are summarized as follows:

- The patterns of solar wind bulk speeds measured by the five spacecraft were very similar and this allows us to identify the same shock event in the different data sets. However, the observations of density, temperature, and the IMF magnitude show less similarity. We found many local structures or inhomogeneities in the observations of all five spacecraft.

- We identified twelve shock events: seven TFSs and five CIR-associated shocks. All the CIR events were detected by the five spacecraft but only two out of the seven

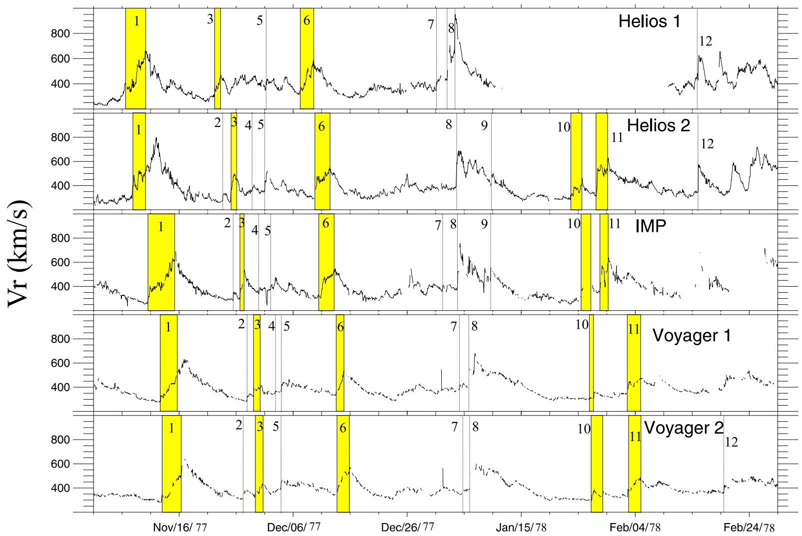

FIGURE 2

Figure 2: Solar wind speed measurements of the five spacecraft from November 1977 to March 1978. The solid cases represent Corotating Interaction Regions (CIRs). The data were obtained from the COHO-Web at the NSSDC.

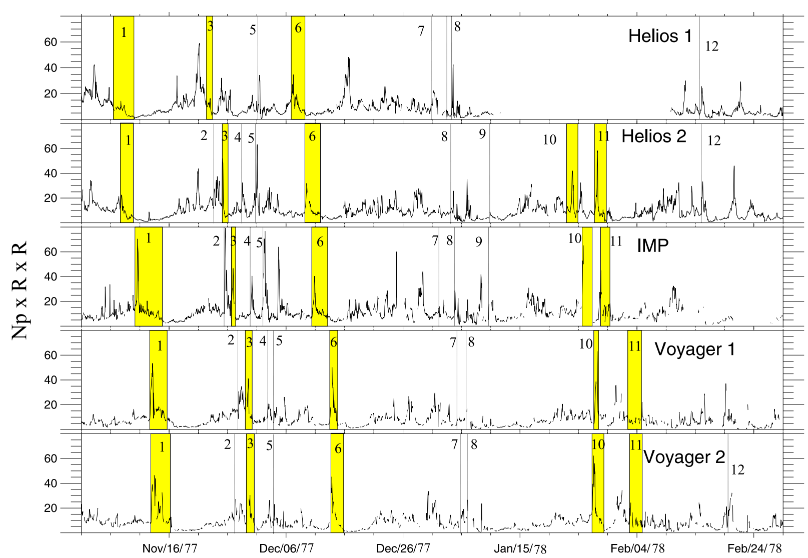

FIGURE 3

Figure 3: Solar wind proton density measurements of the five spacecraft from November 1977 to March 1978. The solid cases represent Corotating Interaction Regions (CIRs).

TFSs were detected by all five spacecraft. The minimum longitudinal extent of the TFSs ($\sim 40°$) was within the range reported in previous studies of two spacecraft observations ($\sim 100°$) [7].

- We found that within the heliocentric range covered by the study, the shock fronts had different local strengths at different positions without any apparent correlation.
- We found a transient shock (TFS 4) where, locally, the shock front disappeared.
- The time lags between the measurements of the same shock from different spacecraft reveals that, in some cases, the form of the shock had strong local deformations.

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