Interplanetary Shocks in the Inner Solar System: Observations with STEREO and MESSENGER During the Deep Solar Minimum of 2008

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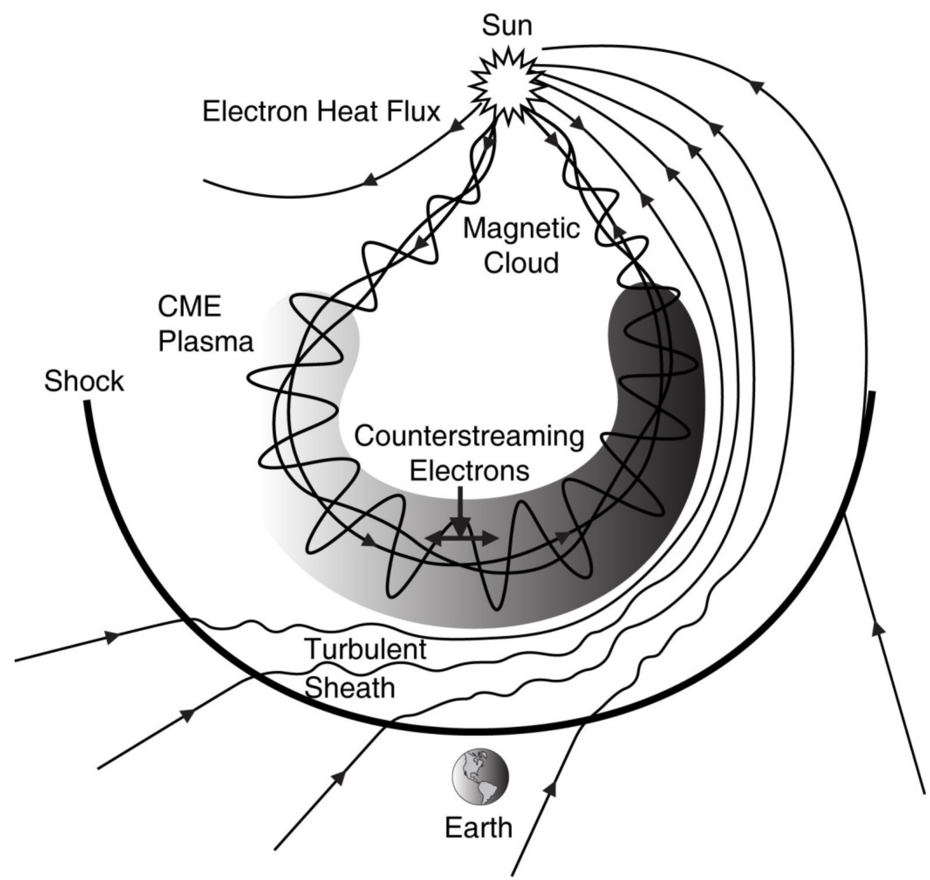
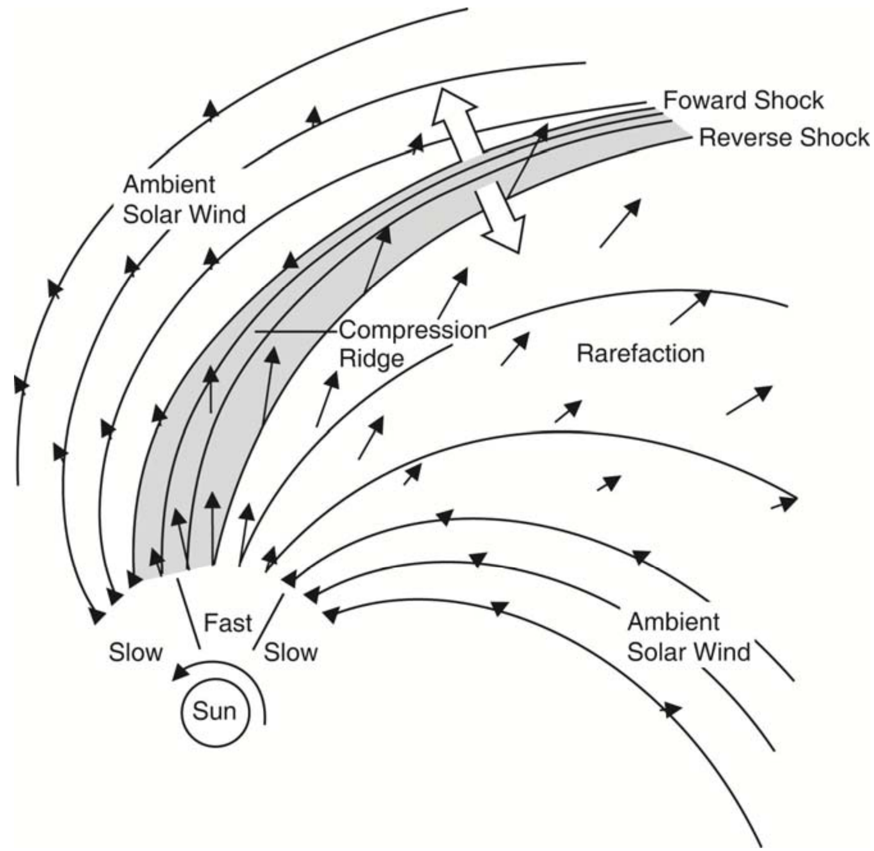
Sources of Interplanetary Shocks: ICMEs

- The most energetic events on the Sun are those that produce Coronal Mass Ejections (CMEs).
- When these ejections reach 1 AU, they consist of a giant magnetic rope moving away from the Sun rapidly, expanding as it does and creating a disturbed plasma sheath and often a leading shock. We call these events ICMEs when detected far from the Sun. The rate of these ejections and their strength are very much solar cycle dependent.

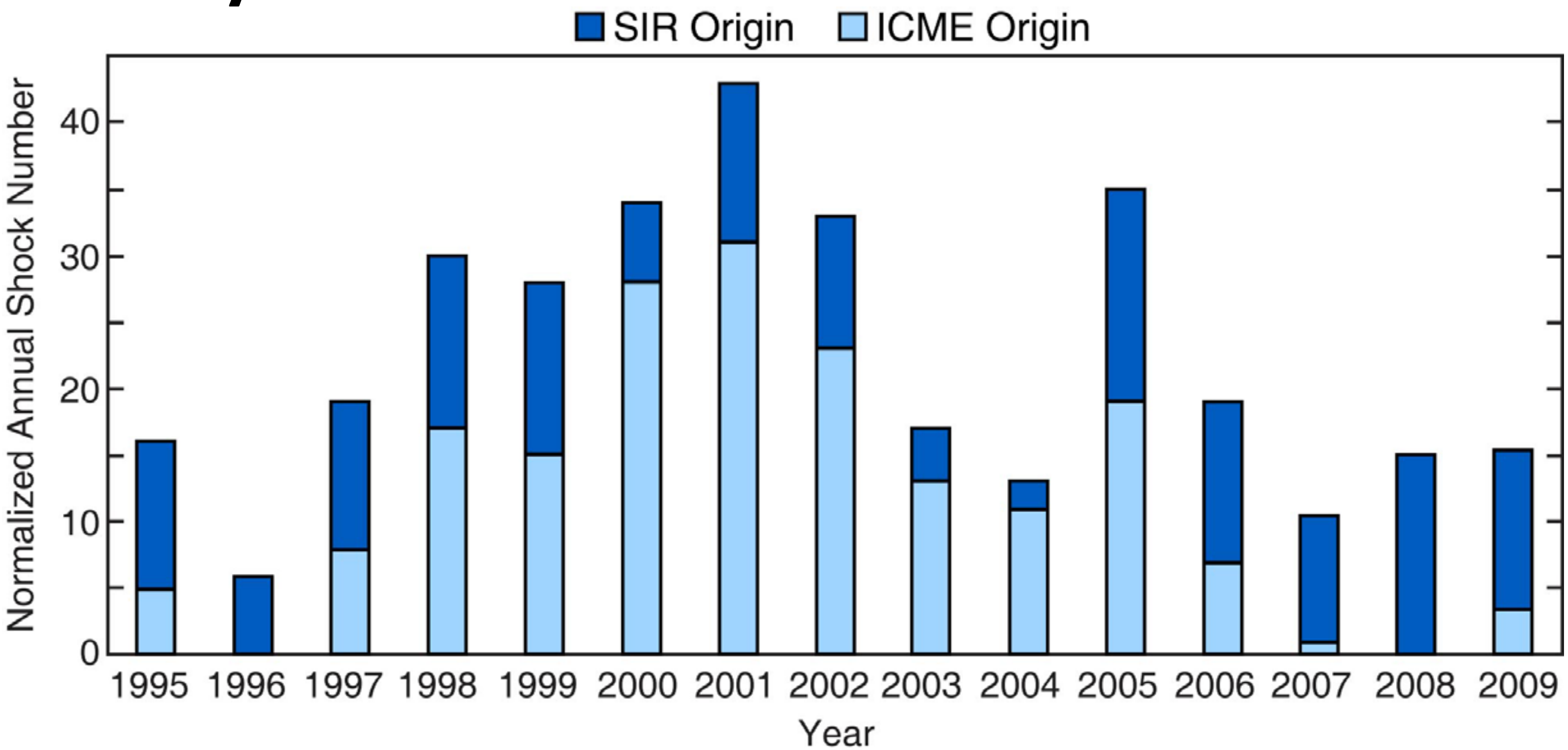


Sources of Interplanetary Shocks: SIRs

- Much more steady are stream interaction regions (SIRs) often referred to as corotating interaction regions (CIRS) when the streams are very steady.
- SIRs get stronger with distance from the Sun and eventually lead to shock formation.
- SIRs are much less sensitive to activity changes during the solar cycle than ICMEs and occur at a near constant rate.



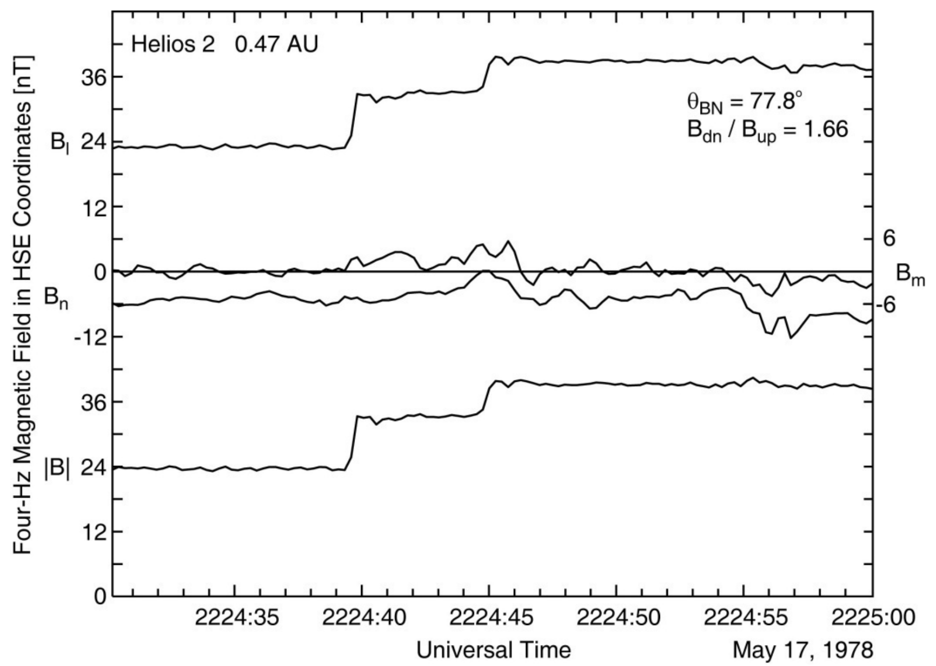
Solar Cycle Variation of Shocks at 1AU



- Wind, ACE and STEREO enable us to study interplanetary shocks for a period of 15 years.
- The number and strength of shocks depends on solar cycle phase and the level of activity on the Sun. When the Sun is producing strong ICMEs, the resultant shocks are strong.
- The extended solar minimum produced weak, mainly SIR-driven shocks at 1 AU. The situation is now beginning to change.

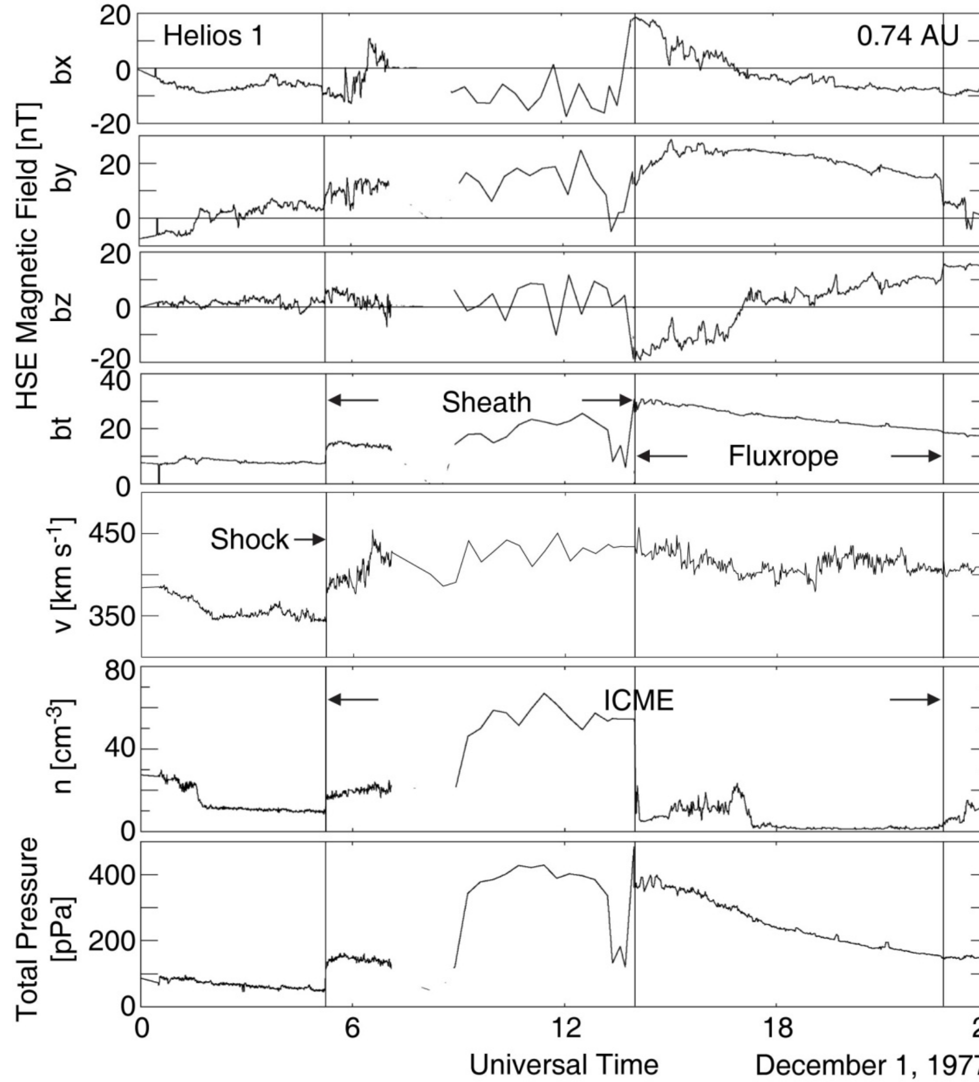
Shock Formation in Inner Heliosphere: Helios 1 and 2 Observations

- The closest measurements to the Sun were made on Helios 1 and 2 starting in 1974 and 1976 respectively going to 0.29 AU.
- Here is an example of a shock growing stronger near 0.47 AU by the overtaking of a leading shock by a trailing shock.
- As they move outward from the Sun, these shocks should grow stronger and weak compressional waves will steepen into shocks.



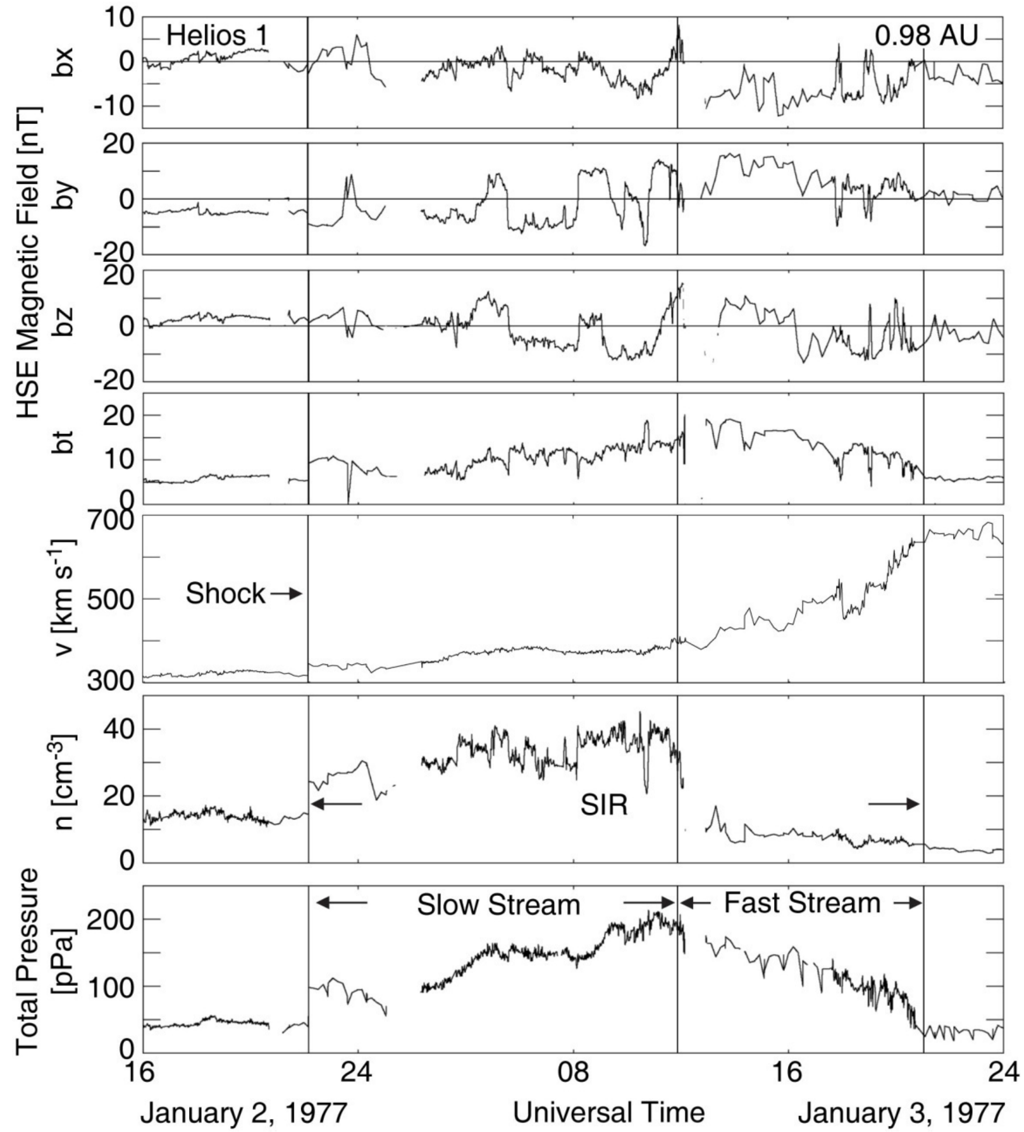
Identifying Shock Drivers with Helios: ICMEs

- We would like to identify what plasma structures lead to shocks in the solar wind.
- When a structure has a sheath and a trailing magnetic flux rope like here, it is probably an ICME.
- Unfortunately, the Helios plasma data is gappy and sometimes the driving mechanism is difficult to identify.



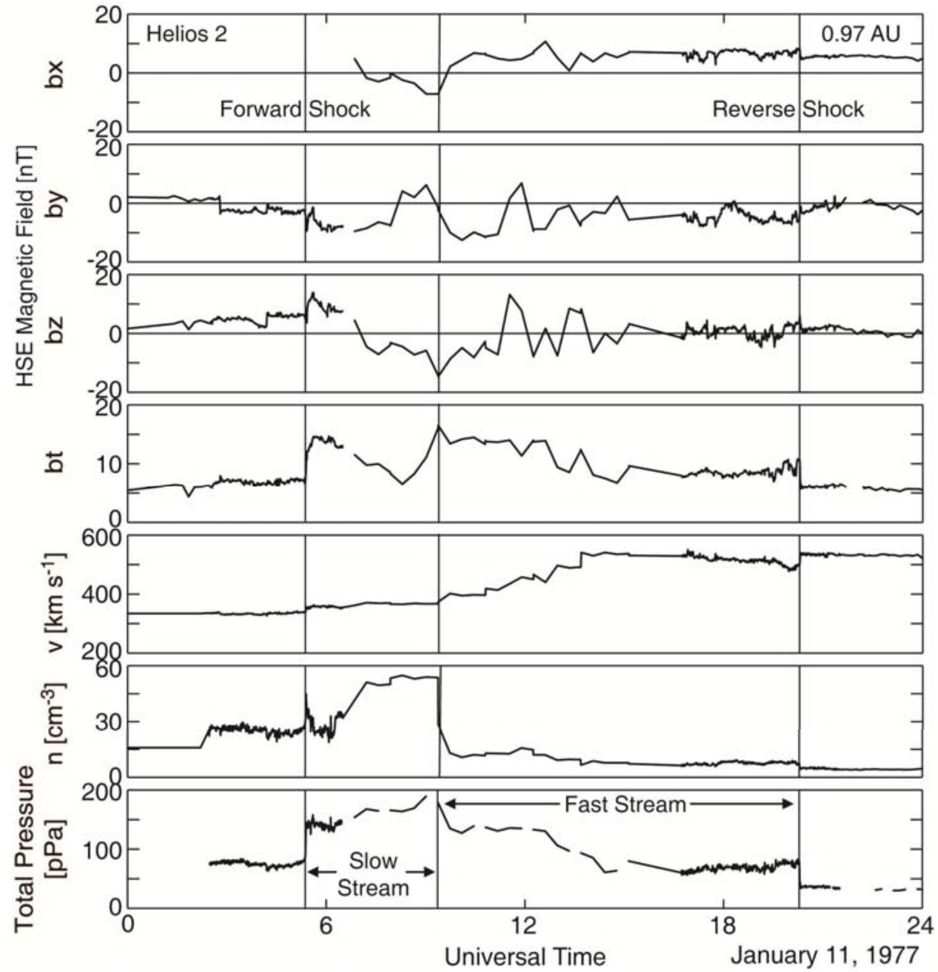
Identifying Shock Drivers with Helios: SIRs

- We can identify a stream interaction by the increasing plasma speed.
- Often a stream interaction leads to a density increase due to compression by the collision. There is also some intrinsic structure in the solar wind. This can be seen in the density panel here where there is an abrupt decrease in density at the stream interface.

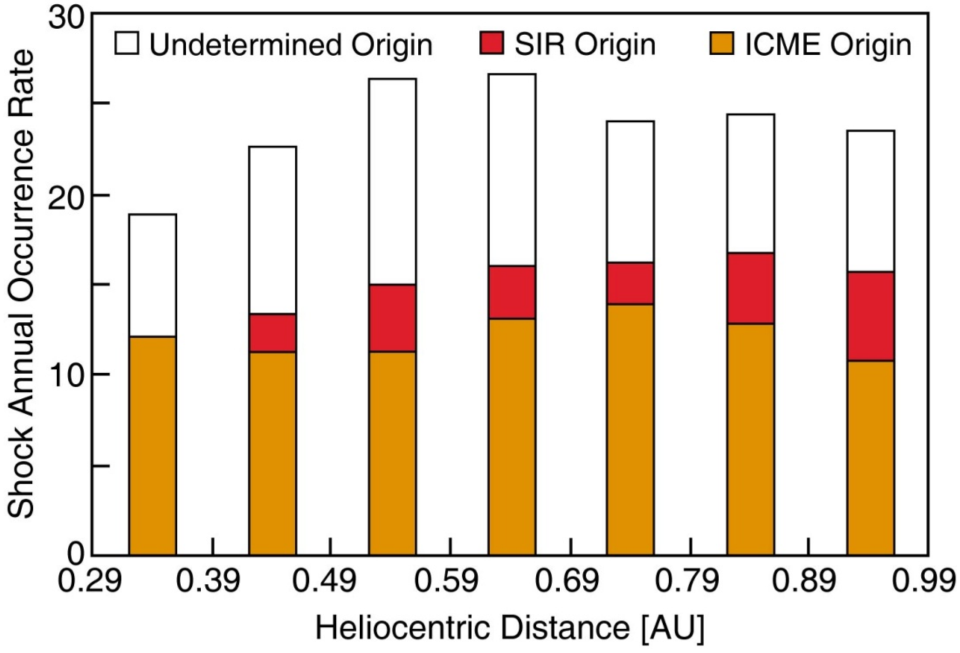


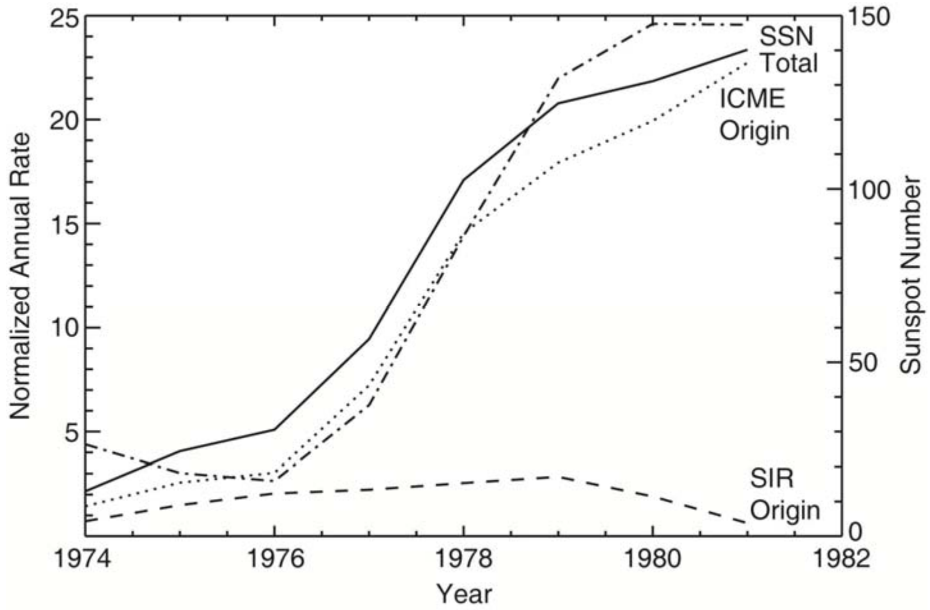
Identifying Shock Drivers with Helios: Forward/Reverse Pair

- Shocks propagating away from the Sun are called forward shocks.
- Shock propagating toward the Sun are called reverse shocks.
- This example has both.



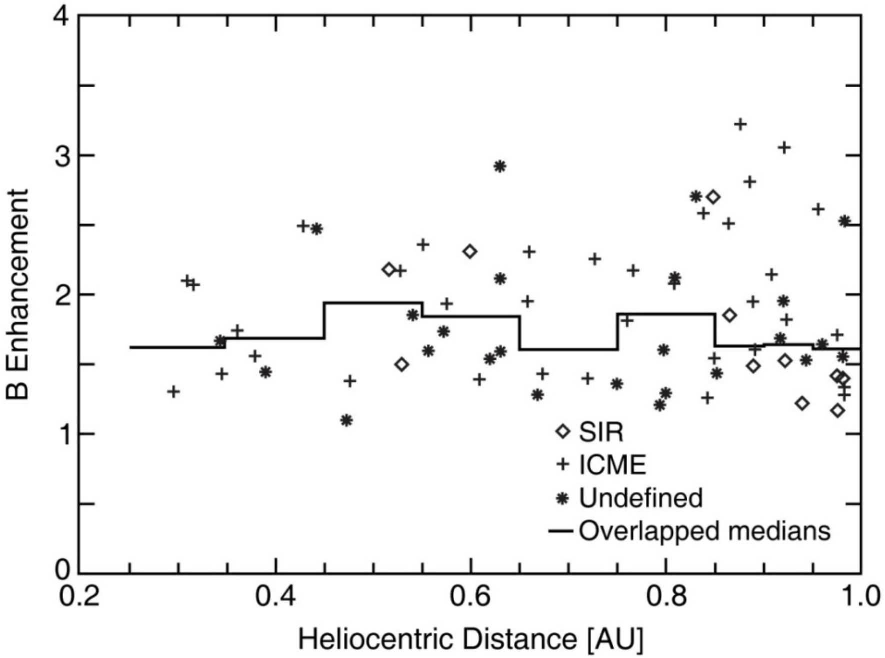
Shock Occurrence Rates in Inner Heliosphere

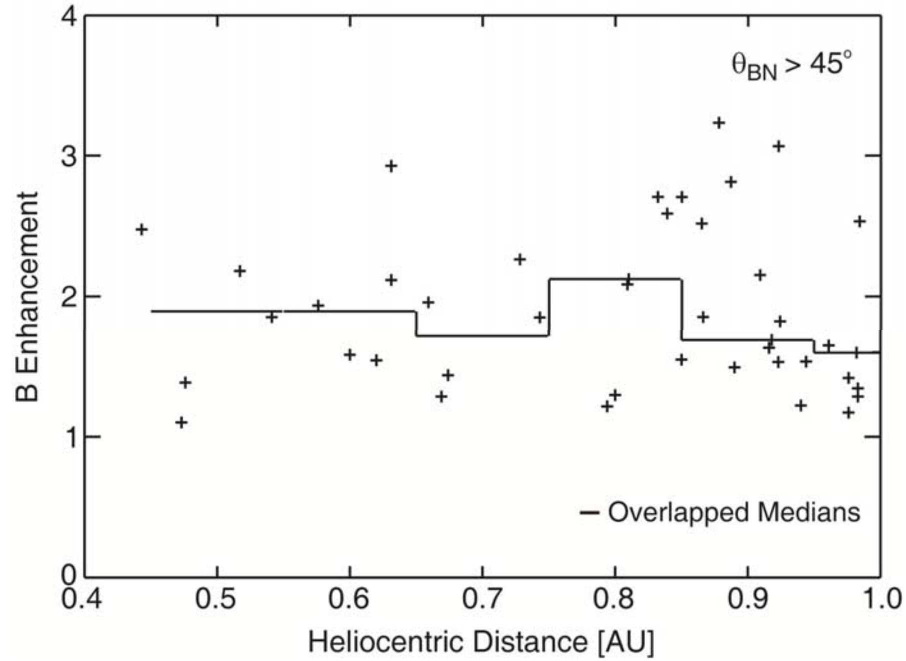




- Similar to observations at 1 AU, Helios data show that most shocks in the inner heliosphere are generated by ICMEs.
- A small fraction, increasing with heliocentric radius, are caused by SIRs.
- The occurrence rate of ICME-associated shocks in the Helios data is strongly correlated with solar activity, as it is at 1 AU.

Shock Strength and Distance

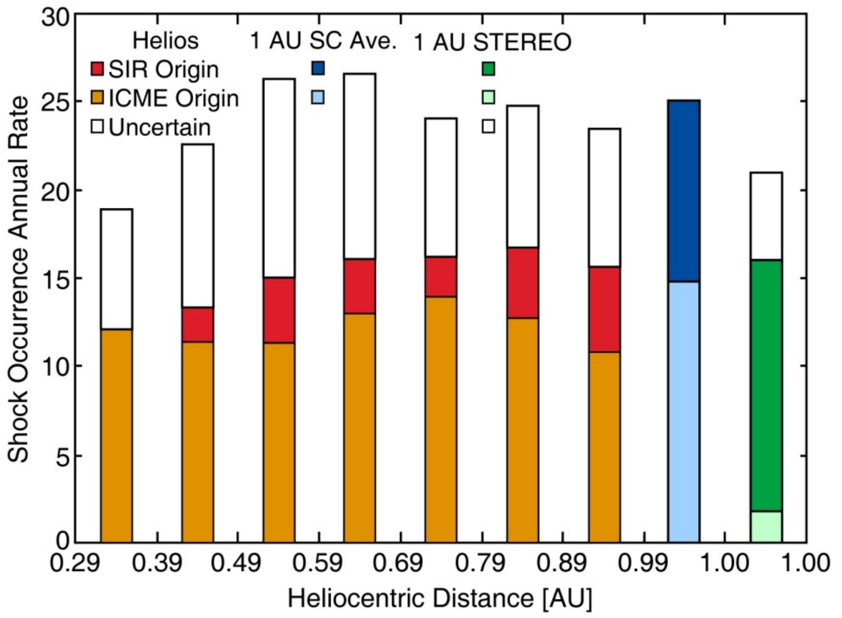




- The jump in magnetic field across the shock can be used as a proxy measure for shock strength when plasma conditions are unknown.
- The strength of the strongest shocks increases with distance from the Sun, but new weak shocks are being created by stream interactions as the solar wind propagates outwards. Hence the median strength does not change much with heliocentric distance.
- If we restrict our study to just quasi-perpendicular shocks ($\theta_{BN} > 45°$), the proxy measure is more accurate. This reduced sample gives the same result, a roughly constant median strength.

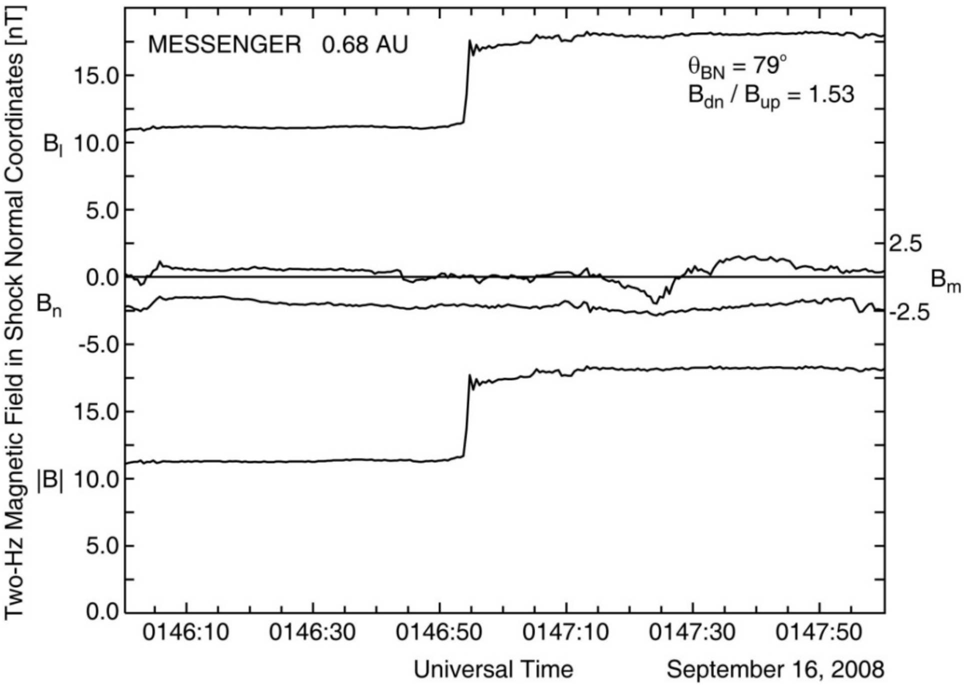
Shock Occurrence Rate: Helios vs. STEREO

- The number of shocks seen by Helios matches well the number observed by spacecraft at 1 AU (Wind and ACE) about 25 per year.
- This plot shows the heliocentric radial variation by shock type.
- As one moves away from the Sun, a larger number of shocks is produced by stream interactions.
- STEREO sees a similar number of shocks, but they are mainly of SIR origin. This is quite different than at Wind and ACE.
- STEREO was launched into the deepest and longest solar minimum in 200 years. Thus it would be helpful if we could measure the radial gradient of shocks contemporaneously with the STEREO data.
- Fortunately we can, using MESSENGER cruise data.



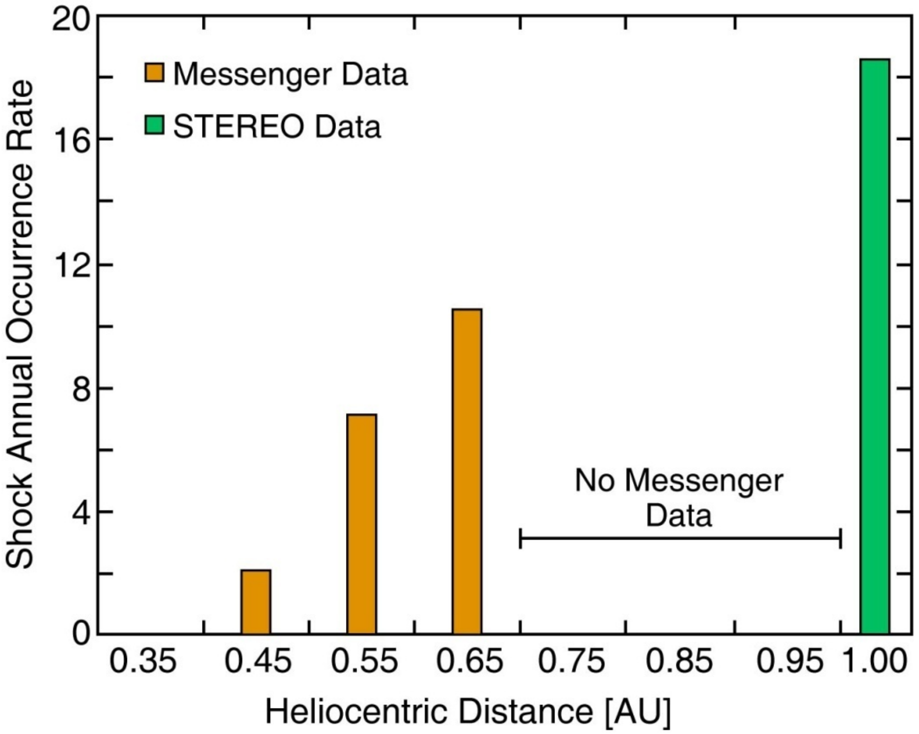
MESSENGER Shock Observations

- MESSENGER was launched in 2004, but its magnetometer boom was not deployed until 2005, so that the early measurements are contaminated by a strong spacecraft field.
- Data in 2007 and thereafter are excellent and can be used to search for shocks.
- The one-Hz data are useful, but two-Hertz data, that are available some of the time, are better.
- There are not many shocks seen during this period. We presume that they are all SIR-driven, but we do not have plasma data to check this.



MESSENGER Shock Rate Compared to STEREO's Rate

- MESSENGER magnetic field data are available in the radial range of 0.3 to 0.7 AU.
- During the available period of observations only 3 events were seen. These are probably all SIR driven considering how low solar activity was at this time.
- We have converted these data to annual rates in three bins.
- While the statistical accuracy of these data are low, they are very consistent with the well-determined STEREO rates at 1 AU.
- It appears that the formation of shocks by SIRs in the inner heliosphere begins about 0.4 AU and their number grows with radial distance.



Summary

- Both ICMEs and SIRs generate shocks in the inner solar system.
- ICME-driven shocks start near the Sun and strengthen as they propagate.
- SIR-driven shocks begin at about 0.4 AU and continue to grow in strength and number with distance.
- ICME-driven shocks are strongly correlated with solar activity, in number and size.
- The predominance of SIR-driven shocks at 1 AU during the cycle 23/24 solar minimum follows directly from the near absence of ICMEs at the time and the growth of SIR shocks with increasing distance beginning at about 0.4 AU.