Interplanetary Field Enhancements: Observations from 0.3 AU to 1 AU

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Abstract. Interplanetary Field Enhancements are rare but very distinct increases in the magnetic field strength, reaching a nearly symmetric cusp-shaped peak. These increases are usually accompanied by a thin central current sheet. Their associations with the perihelion passages of the asteroid 2201 Oljato and with the comet De Vico have led to the hypothesis that these events are associated with the interaction of the solar wind with dust particles. In this paper we examine observations of these events with the Helios 1/2 spacecraft that flew as close to the Sun as 0.29 AU. These events are observed over the entire range of distances studied by Helios 1 and 2. The ponderomotive force exerted by the magnetic field strength decreases with radial distance roughly inversely proportional to the distance squared.

INTRODUCTION

The magnetic field is an agent for transferring stress from the solar wind particles to any obstacles to the solar wind flow. Examples of this action can be found in the interaction with magnetized planets, unmagnetized planets, and comets. In the case of a planetary magnetosphere, the magnetic field in the magnetosheath is compressed downstream of the bow shock and reconnects with the planetary magnetic field. This compression and the tangential stress of reconnection slow the flow, deflect it, and extract momentum from it. The standing shock in the "supersonic" solar wind produces a region of subsonic flow over the forward portion of the obstacle. At an unmagnetized planet with an atmosphere, its ionosphere can act as an obstacle to any time-varying magnetic field. When the ionosphere is highly electrically conducting, very long-term field variations can be excluded from the ionosphere and a magnetic barrier is formed. An interaction very much like that with a magnetized planet ensues, including the formation of a standing bow shock as the supersonic solar wind is deflected around the planet. At a comet, an obstacle is formed by mass loading of the solar wind and momentum exchange between the solar wind and

comet through charge exchange. While this obstacle is quite different from the planetary interactions described above, again a shock is formed around the obstacle, albeit often weaker than that at a planet at the same distance from the Sun. In contrast, interplanetary field enhancements (IFEs), whose field increases should be applying a stress to some obstacle, do not have an associated shock [1]. Thus, they cannot be significantly slowing the solar wind. This is consistent with the fact that their motion appears to be an outward propagation at the solar wind speed.

The association of the occurrence of IFEs with the perihelion passages of asteroid 2201 Oljato in 1980, 1983, and 1986 has led to the hypothesis that these events were associated with the pick-up of dust by the solar wind [2, 3, 4]. An association with comet De Vico strengthened this hypothesis [5]. However, these two objects cannot be responsible for even a significant fraction of the observed IFEs which are distributed around the ecliptic plane [1]. Since any dust "particle" responsible for an IFE could not be detected by a spacecraft because of its small size, the dust hypothesis is consistent with the available observations.

The current paradigm for the transport of dust is shown in Fig. 1. Asteroidal and cometary debris collides and forms smaller and smaller particles as a

function of time and decreasing heliocentric distance. For particles from 1 to 100 microns in the region between the horizontal gray bars, the Poynting-Robertson effect causes particles to spiral inward to where they are evaporated (closer than the vertical gray bar) and picked up by the solar wind, or they are small enough to be acted upon by radiation pressure, electromagnetic effects or plasma drag. These are very small particles with masses of about 10^{-18} kg. These particles would not slow macroscopic regions of the solar wind and no shocks would form. One might also expect that the interaction region will be small; however, these IFEs appear to be as large as the solar wind-Venus interaction. Thus, they represent an enigma.

In this paper, we examine a new set of data for IFEs, the Helios 1 and 2 magnetic field and plasma data that extend from 0.29 AU to 1.0 AU. These observations not only show that IFEs occur *wherever* Helios went, but show a peculiar radial variation in their peak magnetic forces.

It is not the purpose of this paper to reprove everything that is known about IFEs, rather to show how radially distributed observations increase our knowledge of IFEs.

THE MAGNETIC PROFILE OF IFE'S NEAR THE SUN

Most disturbances in the solar wind evolve with increasing radial distance. SIRs steepen and coalesce and ICMEs expand and weaken [7]. One property that IFEs do not share with SIRs and ICMEs is that they do not produce shocks [1, 9] at 0.72 or 1.0 AU. The fact that they have no bow shock is but one of several indications that they are moving outward rapidly. Another indication is the time delay between observations with multiple spacecraft [8, 9]. Near Venus and near Earth, the time delay between observations is that expected if the disturbance is moving outward at the solar wind speed.

One data set that would allow us to study the radial evolution of these structures is the high-resolution magnetic field data from Helios 1 and 2 [10] and the lower resolution plasma data. We have examined that database for the entire mission and recorded the size and duration of each event. An example of an IFE seen by Helios 2 at 0.36 AU is shown in Fig. 2. The duration of the disturbed magnetic field is short, from 2316 to 2340 UT and the central peak is even shorter, about 4 minutes long. There seems to be a weakened noisier magnetic field strength around the central peak as well as a strong central current sheet.
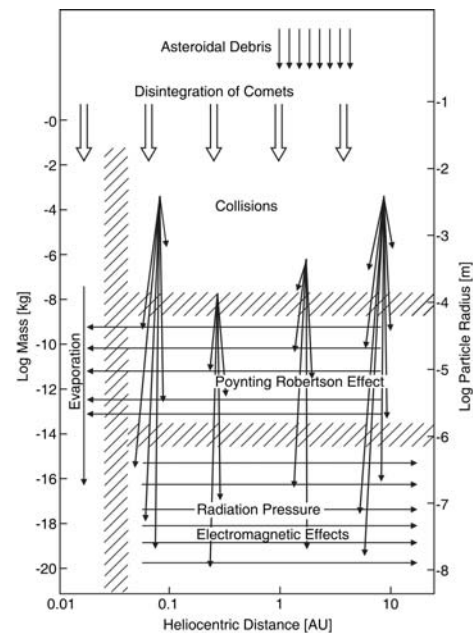
FIGURE 1. Current paradigm of dust transport in the solar system. See text for discussion (adapted from [6]).
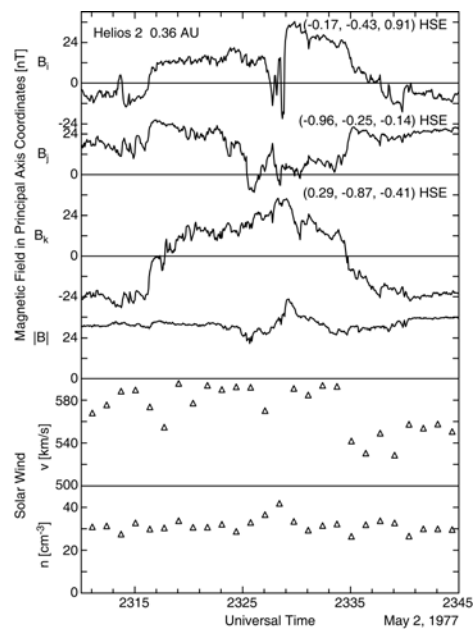
FIGURE 2. Magnetic field data with the time resolution of about one vector every 4 seconds from Helios 2 at 0.36 AU during the passage of an interplanetary field enhancement. The data are expressed in principal axis (i, j, k) coordinates. This coordinate system has the change in magnetic field at the current sheet maximum in the i direction. The minimum variance is in the k direction. The orientation of each axis of this coordinate system is given on the figure in Helios Solar Ecliptic (HSE) coordinates with X to the Sun and Z along the ecliptic pole. The bottom two panels show measurements of the solar wind speed and density.
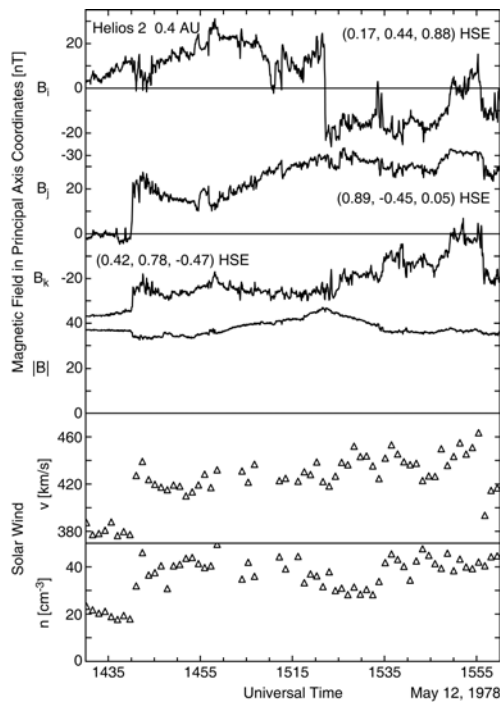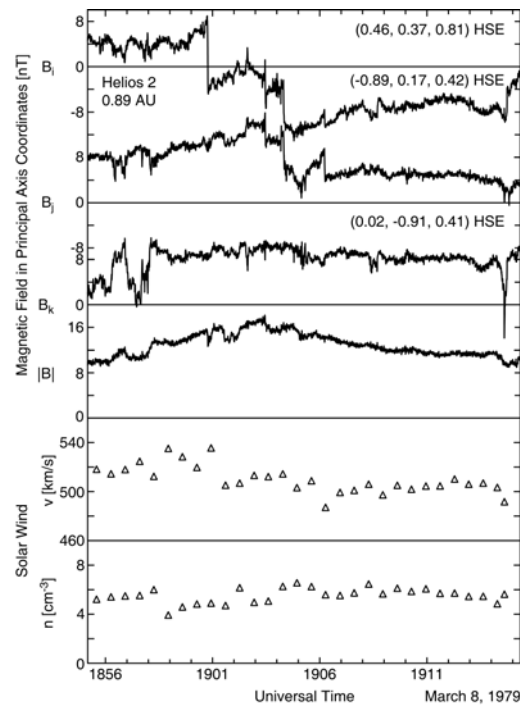
FIGURE 3. An example of an IFE at 0.4 AU seen by Helios 2. Magnetic field data have the time resolution of 2.57 seconds. Comments of the caption of Fig. 2 apply.

The solar wind proton speed and density are displayed in the bottom two panels. During the central field increase, the solar wind speed is constant here. This structure is not accelerating or decelerating. There is a slight density rise near the center of the event, but not aligned with the increase.

A second event is shown in Fig. 3 at 0.40 AU. Here, the disturbed interval is over an hour, from 1440 to 1555, and the central field enhancement is about 35 minutes long. Again, there is a strong central current sheet and there is a noisier slightly weakened magnetic field strength surrounding the central field enhancement. The solar wind proton speed and density are shown in the bottom two panels. At the leading "edge" of the IFE, the density increases and the field strength decreases, but near the characteristic central peak field strength, there is no compression in the density or slow down in the flow. The discontinuity at 1440 UT is not a shock because a shock cannot reverse any component of the magnetic field as happens here in the j component. This is a tangential discontinuity.

A third event is shown in Fig. 4 at 0.89 AU. Again, we show the solar wind speed and density in the bottom two panels. The speed and density are almost constant and do not reflect the peaked field structure that marks the IFE. Again, the field is compressed but the plasma is not compressed. Again, a trapped charged dust particle could provide that obstacle.


FIGURE 4. An example of an IFE at 0.89 AU seen by Helios 2 with the time resolution of 0.58 seconds. Comments of the caption of Fig. 2 apply.

Since we identify IFEs by their characteristic magnetic field enhancement, we should measure their duration by the length of time the field is enhanced. We have done this for all our IFE encounters in Fig. 5. The solid line shows the median duration from 0.3 AU to 1 AU in 0.1 AU steps. The median duration hardly changes. This is consistent with these events moving outward at constant speed if they also did not expand.
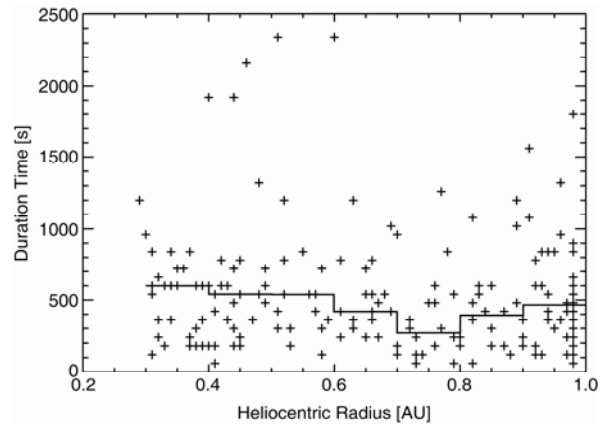
FIGURE 5. The duration of the passage of the central peak versus heliocentric distance.

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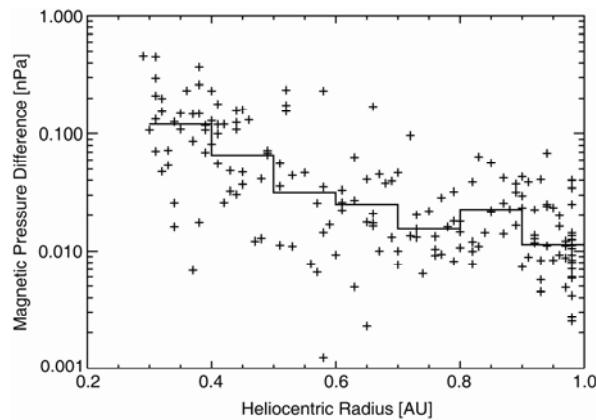
FIGURE 6. The pressure difference in the magnetic field between the central peak and the surrounding magnetic field versus heliocentric distance.

The pressure exerted by the field increase must work in the forward and backward directions. It must be propelling something forward (mass against the Sun's gravity?) and extracting moment from the solar wind in the other direction. Thus it is an agent for transferring momentum. We can calculate the pressure difference from the magnetic pressure in the central peak (whose maximum we may miss if we cross the structure away from the center) by subtracting the background magnetic pressure. This pressure difference is shown in Fig. 6. Surprisingly, the force varies as roughly the inverse square of the heliocentric distance. Another force that falls off this way is the Sun's gravitational force. Thus the IFE pressure could be balancing mass against solar gravity but we do not have a model for how this could take place on the microscopic level.

SUMMARY AND DISCUSSION

We have used the Helios high-resolution magnetometer and plasma data to provide further constraints on the cause of interplanetary field enhancements. The three examples we show all have central field enhancements and central current sheets. We have used a current sheet-ordered coordinate system in these displays. If these were used in the Earth's magnetotail or that of a comet, the direction of the field that contained the largest change would be the direction of the "draped" tail. In all these cases (picked at random) the direction of this axis lies near the ecliptic pole. We have not yet performed enough of these exercises to determine the statistical significance of this result. The result of which we are most certain is that there is never a bow shock so the disturbance is moving outward with the solar wind. The magnetic field has the signature of a compression, but the plasma

does not. Structures somewhat resembling this have been produced in hybrid simulations [11], but these simulations do not include solar gravity. There is clearly much more to be understood about these events.

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