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Large-scale solar wind density enhancement and its boundaries: Helios 1, 2 and IMP 8 observations

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Abstract

In the present paper, we investigate a large pulse in the solar wind density observed on April 1–2, 1977 by the Helios 1, 2 probes and 2 days later by the IMP 8 spacecraft in the "line-up" condition (all three spacecraft had the positions along the Sun–Earth line). In this pulse the strong enhancement in density (~50% relative to the undisturbed level) was not accompanied by significant changes in other main solar wind parameters. The outcomes of detailed analysis of physical properties as well as of geometrical features of the observed plasma pulse structure are discussed. One of the characteristic peculiarities of this pulse was its sharp boundaries (with durations of several minutes only). The main scientific result of our study is that the trailing edge of the pulse was found to be very stable (conserved its shape and duration) propagating over as large distance as 0.6 AU (90×10^6 km) or during 2.3 days of the solar wind motion.

Keywords: Interplanetary physics; Solar wind

1. Introduction

The investigation of solar wind structure dynamics during their motion from the solar corona through the solar system is very important. On the one hand, such a study may lead to a better understanding of the mechanisms controlling the fundamental processes in space plasma. On the other hand, it is a necessary part for space weather prediction based on observations made in areas located far away from the Earth.

In the case of spherically symmetric expansion, the transverse size of any solar wind volume changes proportionally to the distance from the Sun and the radial size of the structure volume changes proportionally to the difference of speeds at the leading and trailing fronts.

However, the experimental and theoretical data on dynamics of interplanetary magnetic field (IMF) structures show that in addition to simple geometric changes connected with solar wind expansion, there are mechanisms resulting in redistribution of its scales: a portion of small-scale structures increases due to nonlinear processes in interplanetary space and a portion of large-scale structures of solar origin significantly decreases (see, for example, the review of Zelenyi and Milovanov, 2004 and references therein). Nevertheless, theoretical consideration and experimental data demonstrate that under some conditions the small-scale and middle-scale solar wind structure can be stable and their boundaries can conserve their shape and durations or even become steeper during their motion between the Sun and spacecraft (see, for example, Sagdeev, 1966).

Amongst the large-scale interplanetary phenomena which are widely discussed in the literature there are transient features such as magnetic clouds (MC) and recurrent features such as corotating interaction regions (CIR) (Burlaga, 1995; Yermolaev, 1991).

MCs are suggested to be interplanetary manifestations of coronal mass ejections (CME), and the dynamics and interactions of CME with one another and with the ambient solar wind plasma are studied in many papers

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(see, for example, the special issue of Space Sciences Review, N6, 2006). CIRs are formed by the interaction of fast and slow solar wind streams and they were investigated in detail (see, for example, Geophysical Monograph, vol. 167, 2006).

However, the dynamics of a great number of other interplanetary large- and middle-scale streams remains rather unknown. The most evident and reliable method of such study is the comparison of simultaneous observations of solar wind structures at rather distant points in space under the condition that the same plasma volume passes through several spacecraft. But in spite of the significance of this problem, there have been only a few experimental results on this field.

We will limit our analysis to only the inner heliosphere (i.e. from the solar corona to the Earth's orbit). One of the first results concerning this subject was obtained on the basis of the comparison of solar wind parameters measured onboard the two spacecraft Helios 1 and 2, operating simultaneously in 1976–1980 on two separated heliocentric orbits (Schwenn and Marsch, 1990). In particular, in articles (Schwenn, 1983; Schwartz and Marsch, 1983) it was shown that in a few events, when these spacecraft were located along the same radial line, and were separated by solar ecliptic latitude of no more than 5°, hourly averaged solar wind velocity values measured on both spacecraft were in a close agreement, although the distance between them was as large as 30×10^6 km. However, such comparisons were carried out only for the solar wind velocity and only for rather large-scale structures (with durations of about several days).

The detailed investigation of the similarity of middle-scale structures (with durations of about several hours) by multi-spacecraft observations for solar wind ion flux (or density) as well as for solar wind velocity was presented in several papers (for example, Paularena et al., 1998; Dalin et al., 2002a, b). On the basis of large statistics it was shown that such middle-scale structures usually have very similar behavior for solar wind parameters (the average correlation coefficient is 0.73) for two points separated up to 10^6 km along the Sun–Earth line and as far as several hundred thousands km in the perpendicular direction.

The next progress in solving of this problem was from observations of small-scale solar wind structures, for example, sharp and large plasma density changes with the durations of their fronts equal to several minutes or seconds (Riazantseva et al., 2003a, 2005a). It was shown that for a considerable part of the events even for the sharpest small-scale structures the boundaries are able to keep their shape, amplitude, and duration during a solar wind motion from the libration point *L*1 to the bow shock (Zastenker et al., 2006).

It is important to note that these sharp density changes are not connected to well-known events as CME and CIR and are more often observed in the dense solar wind (Riazantseva et al., 2005b). An attempt has been made (Aleshin et al., 2006) to explain the stability of very sharp changes of the solar wind plasma density by a jump of the electrostatic potential at the density change. But this idea has not been checked yet by comparison with an experiment.

However, it is clear that, using data from the ISTP spacecraft (IMP 8, WIND, Geotail, Interball-1, ACE, SOHO), it is impossible to obtain information on distances of more than 10^6 km along the solar wind flow direction between the measurement points. That is why we made a search for structures with rather sharp boundaries in the Helios 1, 2 data. For such observations the similarity (or difference) in the behavior of solar wind parameters can be considered for rather large distances between the spacecraft, significantly exceeding 10^6 km. The results of the investigation of the solar wind dynamics for one event are presented in this paper.

2. Data sources and analysis

In the present work, the main solar wind parameters (velocity, density, temperature and IMF) are taken from measurements of Helios 1 and 2 probes (Porsche, 1977) as well as of the IMP 8 spacecraft (Lazarus and Paularena, 1996). The temporal resolution of the presented data is 40 and 60 s for the Helios data and for IMP 8 data, respectively.

A large pulse in solar wind density was observed on April 1–2, 1977 by Helios 1, 2 and on April 3–4, 1977 by the IMP 8 spacecraft. The scheme of spacecraft positions in the ecliptic plane is presented in Fig. 1. At that time, Helios

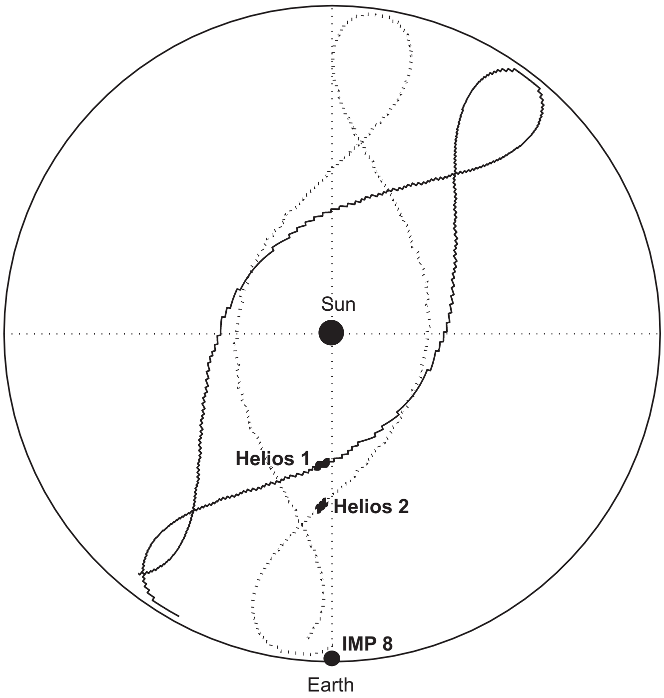

Fig. 1. Heliospheric Helios 1 (solid line), Helios 2 (dotted line) trajectories in 1977 projected onto ecliptic plane. IMP 8 spacecraft trajectory is close to the Earth and it is not shown. Heavy solid lines are the parts of Helios 1 and 2 trajectories on April 1–2.

1 and 2 were located 0.60 AU (90×10^6 km) and 0.48 AU (72×10^6 km) apart from the Earth, respectively. They were close to each other in solar longitude (within 5°) and latitude (within 0.2°), (so called a radial "line-up") and, that is the most important, close to the Sun–Earth line.

The Helios probes were separated by a rather large radial distance of 0.12 AU (18×10^6 km). IMP 8 was located in the near-Earth orbit and therefore at the above stated distances from Helios 1 and 2 probes, respectively. If three spacecrafts are expected to pass through a common solar wind volume, the positions of these spacecraft provide a possibility to investigate temporal variations of an observed solar wind structure during its motion between the spacecraft. At the same time, the separating distance between the Helios probes in the direction perpendicular to the Sun–Earth line was rather large (changing from 0.8×10^6 to 2×10^6 km) allowing us to draw some conclusions concerning spatial inhomogeneities of the plasma pulse.

Fig. 2 illustrates the solar wind density observed by Helios 1, 2 and IMP 8 when the Helios probes were relatively close to the Sun–Earth line on April 3, 1977. These data sets are plotted without any time-shift due to the propagation speed of the solar wind between three spacecraft. The ovals in the upper panel indicate the large plasma density pulse observed by the Helios probes, whereas the oval in the lower panel contours the assumed plasma density pulse seen by IMP 8.

Although the behavior of the solar wind plasma density seen by IMP 8 is rather different from that seen by the Helios probes, the detailed analysis (based on the average solar wind propagation time from Helios 2 to IMP 8 equal to ~1.8 days) allowed us to identify the studied plasma density pulse seen by IMP 8; other candidates are much less similar.

Fig. 3a (upper panel) demonstrates the plasma density pulse as seen by the Helios probes and IMP 8 in detail. The lower panel illustrates the behavior of total plasma pressure (thermal + magnetic ones) across the pulse. The total pressure is estimated from the IMP 8 and Helios 1 data. The Helios data are recalculated to the near-Earth orbit solar wind parameters.

Fig. 3b demonstrates the basic plasma and IMF parameters (the Helios1, 2 and IMP 8 data) of the large plasma pulse in the solar wind. The first, second, and third panels are the bulk speed, proton temperature, and the field magnitude, respectively. Unfortunately, the Helios 2 magnetic field data are almost absent for the considered period. The boundaries of the pulse are marked by arrows 1 and 2. For plotting both Fig. 3a,b, the Helios 1 data sets are shifted ahead to Helios 2 by an average time (11.3 h) of the solar wind propagation between the two probes. The average solar wind speed (450 km/s) over the considered time interval was taken for this estimation. The IMP 8 data are also shifted to Helios 2 to an average time of 43.6 h, but in this case, it is necessary to add an additional time shift of

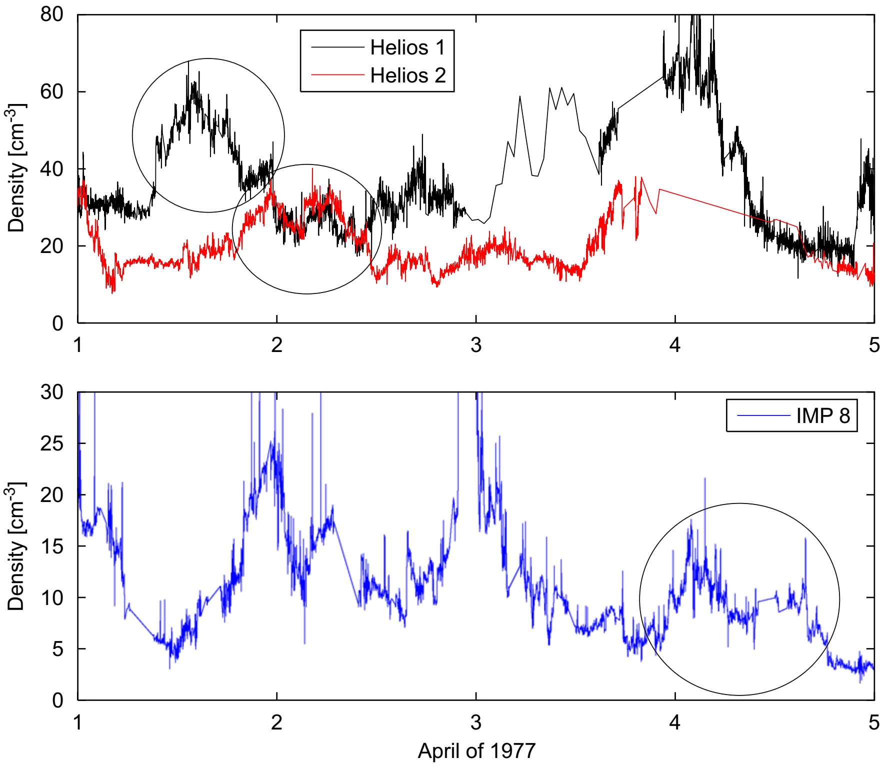

Fig. 2. Time series of the solar wind density as observed by Helios 1, 2 and IMP 8 when the Helios probes were relatively close to the Sun–Earth line on April 1–3, 1977. Two ovals at the upper panel indicate the large plasma density pulse by the Helios probes studied here: the oval at the lower panel contours the similar plasma density pulse seen by IMP 8.

12 h to the best fitting of data sets. The reason of this additional shift is discussed below.

The large pulse observed by two Helios probes is characterized by an enhancement of the solar wind density by a factor of 1.5 relative to the undisturbed (background) value, and the duration of this pulse is about 14 h. The prominent feature of this pulse is its very sharp leading (marked as 1) and trailing (marked as 2) edges seen by Helios 1. The trailing edge is seen to be quite stable (i.e., it keeps its shape) during about of 11.3 h of the structure moving between Helios 1 and 2, and during of 55.6 h (43.6 + 12) between Helios 2 and IMP 8. Note that duration of the trailing edge is very short (compared with the pulse duration) and is equal to about 3–7 min at all three spacecraft. At the same time, the slope of the leading edge decreases and this edge arrives to Helios 2 approximately 1 h earlier than estimated from the solar wind speed.

A more intriguing feature of this pulse is the changing of the density distribution inside the pulse structure: Helios 1 measurements demonstrate one maximum of the plasma density (around 01:30 UT on April 2), while the Helios 2 data sets show two maxima (at 23:00 UT on April 1 and at 04:00 UT on April 2). The plasma structure observed by Helios 2 has an additional sharp front at 03:00 UT on April 2 separating these two maxima in the plasma density. Note that the solar wind speed increases slowly inside the plasma pulse from 400 up to 500 km/s without any sharp changes.

Also the proton temperature enhances slowly from 150,000 up to 400,000 K with no sharp variations as well. The IMF demonstrates strong variations of all components (with a sign reversal) at the time of passing of the leading edge, while the trailing edge is accompanied with rather moderate changes of the magnetic field.

To classify types of discontinuities at the boundaries of the large plasma pulse, we have used the Rankine–Hugoniot relations and applied the minimum variance analysis to the Helios 1 data to estimate the normal direction of each discontinuity (Song and Russell, 1999).

The normal component of the magnetic field to the leading edge surface is found to be relatively close to zero, i.e., the angle between the normal to the surface and the magnetic field at the leading edge is equal to 80 ± 4°. The normal component of the flow velocity is 9.5 km/s across the surface of the leading edge. A most important feature is that the total pressure does not remain constant across the leading edge (see the lower panel of Fig. 3a). Thus, this change of solar wind parameters is neither a contact nor a tangential nor a rotational discontinuity. It is difficult to be sure what type of discontinuity exists at the leading edge.

The trailing edge has the following characteristics. The normal component of the magnetic field to the trailing edge

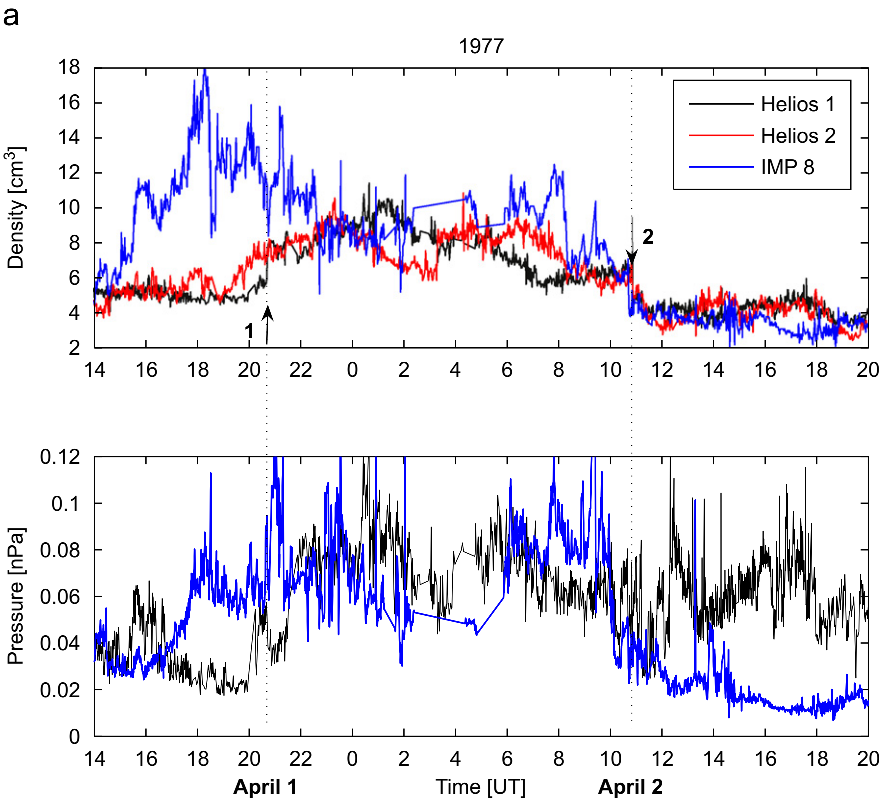

Fig. 3. (a) Upper panel: the plasma density pulse in detail seen by the Helios probes and IMP 8. The boundaries of the pulse are marked by arrows at 1 and 2. The lower panel: the total plasma pressure across the pulse estimated by the Helios 1 data and the IMP 8 data. (b) The basic plasma and magnetic field parameters as observed by Helios1, 2 and IMP 8. The boundaries of the pulse are marked by arrows at 1 and 2. Three lower panels show the geocentric–solar–ecliptic coordinates of the Helios probes.

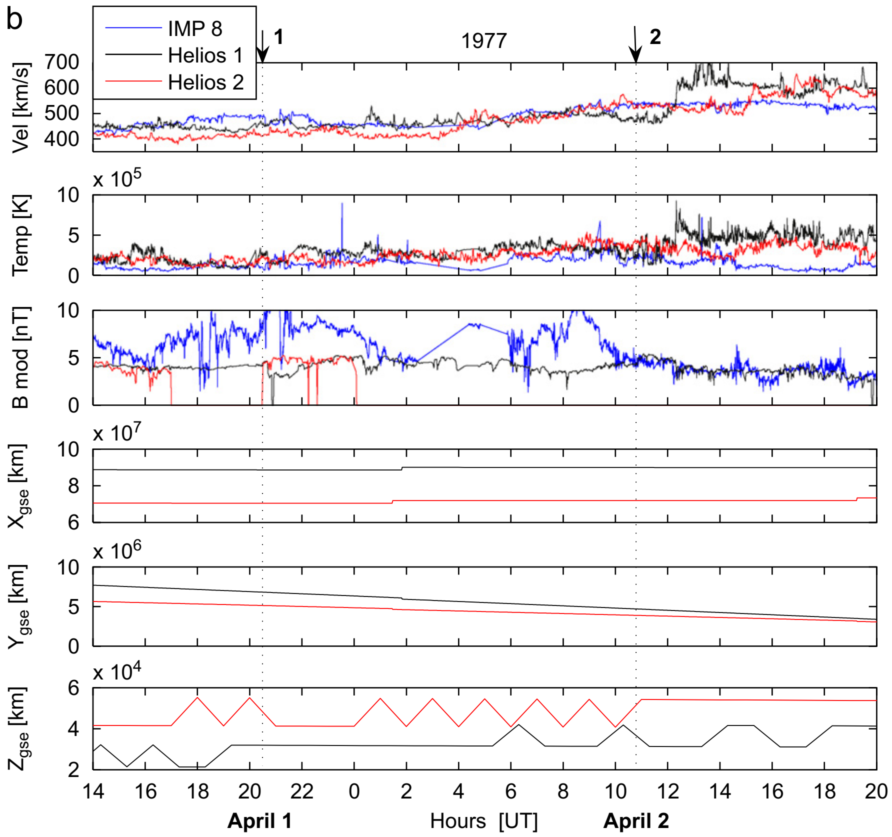

Fig. 3. (*Continued*)

surface is about zero (the angle between the normal and the magnetic field at the trailing edge is equal to 93 ± 1°), the normal component of the flow velocity is only 3.0 km/s across the surface of the trailing edge, and the total pressure remains approximately constant across the trailing edge. Thus, in a first approximation, we can conclude that the trailing edge is an example of a tangential discontinuity.

3. Discussion

The presented data demonstrate the changes and conservation of plasma structures on large separation distances among three spacecraft. The three observational facts are necessary to be discussed:

(a) decreasing of the steepness of the leading edge;
(b) evolution of the density distribution inside the structure;
(c) additional time delay of 12 h to the best fitting of the IMP 8 data to the Helios 2 data.

We can suggest three following hypotheses (which are discussed below) to explain the variability of the plasma parameters:

(1) spatial expansion of the plasma at the leading edge and inside the structure during its motion between both Helios probes and from Helios 1, 2 to IMP 8;
(2) Helios 1 and 2 crossed different spatial areas with various plasma density distributions;
(3) inclination of the sharp plasma boundaries exists.

3.1. *Spatial expansion of the plasma at the leading edge and inside the structure*

This explanation is valid if the total pressure P_{tot} (plasma thermal pressure + magnetic pressure) inside the plasma pulse structure dominates over the total pressure outside the pulse (see the lower panel of Fig. 3a).

We suggest that the spatial expansion of the leading edge is possible due to the fact that the total pressure (by Helios 1) inside the structure near the leading edge (~0.07–0.08 nPa at 22:00–02:00 UT on April 1–2) is about twice P_{tot} outside the structure (~0.03–0.04 nPa at 14:00–19:00 UT on April 1). On the other hand, P_{tot} is nearly the same (on the average 0.06 nPa) before and after the trailing edge of the plasma pulse, thus it implies no dynamical changes, and it is perfectly confirmed by the observed data.

One can verify this conclusion by comparing the velocity of the leading edge expansion to the Alfvén and sound speeds in the solar wind. The expansion velocity V_1 relative to the average velocity of the solar wind is expressed as follows:

$V_1 = L/(L/V_0 - \Delta t) - V_0$, where V_0 is the average speed of the solar wind inside the plasma pulse, equal to 450 km/s, L

is the distance between the spacecraft, about 18×10^6 km, Δt is the time difference of record of the leading edge by Helios 1 and 2, equal to about 1 h. One can find that the expansion velocity V_1 of the leading edge is equal to 42 km/s. This value is smaller than the Alfvén and sound speeds inside the plasma structure close to the leading edge which are 74 and 52 km/s, respectively. Since the leading edge does not represent a shock, the hypothesis of the spatial expansion of the plasma structure along the Sun–Earth line seems to be realistic.

We can note another interesting feature of the expansion of the structure. If there is a 1 h shift (due to the expansion velocity of 42 km/s) in registering of the leading edge between Helios 1 and 2 on the distance of 18×10^6 km, then there should be a delay of 4 h on the distance of 72×10^6 km, i.e., between Helios 2 and IMP 8. This is exactly what we observe in Fig. 3a: there is a sharp jump of the plasma density in the IMP 8 data at 16:00 UT on April 1 which leads the leading edge (by the Helios 2 data) by about 4 h. Thus, an excess pressure at the leading edge inside the structure seems to lead to the expansion of the structure that, in turn, can explain an apparent discrepancy in registering of the leading edge between Helios 1 and 2, and then between Helios 2 and IMP 8.

Fig. 3a illustrates that the central peaks of two maxima are separated by about 5 h. One can estimate that the first maximum should move by 80 km/s faster and the second one by 80 km/s slower than the background flow. The Alfvén and sound speeds for the conditions inside the pulse structure between the two maxima are 102 and 83 km/s, respectively. This supports the idea that dynamic changes of the plasma structure during its motion among the spacecraft could really take place.

Note that since the solar wind speed is increasing slowly inside the plasma pulse from 400 up to 500 km/s, one can assume that this may be a cause of an evolution of the plasma inside the density pulse. Using a point-to-point shift of the Helios 1 data to the Helios 2 data (not shown in Fig. 3a), we have verified that this increasing velocity does not lead to possible evolution of the structure and appearance of the density dip in the Helios 2 data. Also, since the speed at the trailing edge exceeds the speed at the leading edge, one could expect that the plasma structure would have been compressed, but in reality, the data demonstrate to us the conservation of the duration of the density pulse (or even a slow expansion) with more smooth leading edge seen by Helios 2 (see Fig. 3a).

3.2. Helios 1 and 2 crossed different spatial areas with various plasma density distributions

Under this hypothesis, one can suggest the presence of the plasma structure of a complicated form that could explain the observed feature: two maxima in the plasma density distribution observed by Helios 2. Such a structure can be represented by the V-like shape in the ecliptic plane, which has one broad maximum of density at its base and two narrow maxima at its tops, with the base passing through Helios 1 and the two tops passing through Helios 2 (Fig. 4). In this case, Helios 1 would register one density maximum of a narrower spatial area, while Helios 2 would recorder two maxima and an apparent expansion of such a V-like structure. We believe that this is exactly what the observed data demonstrate. Note that the separation distance between Helios 1 and 2 along the Y-axis changing from 2×10^6 up to 0.8×10^6 km at the leading and trailing edges is quite large. Thus, the difference in spatial locations of the two probes along the Y-axis provides the principal reason for the observation of such a plasma structure.

We suggest that this structure has a shape of a 3-D fold and its tops are connected at some distance (along the Z-axis) relative to the ecliptic plane. It is important to note that all three spacecraft are situated very close to each other in the ecliptic plane, with a separation distance along the Z-axis exceeding no more than 20,000 km (see Fig. 3b), that is too small to draw any conclusions concerning the

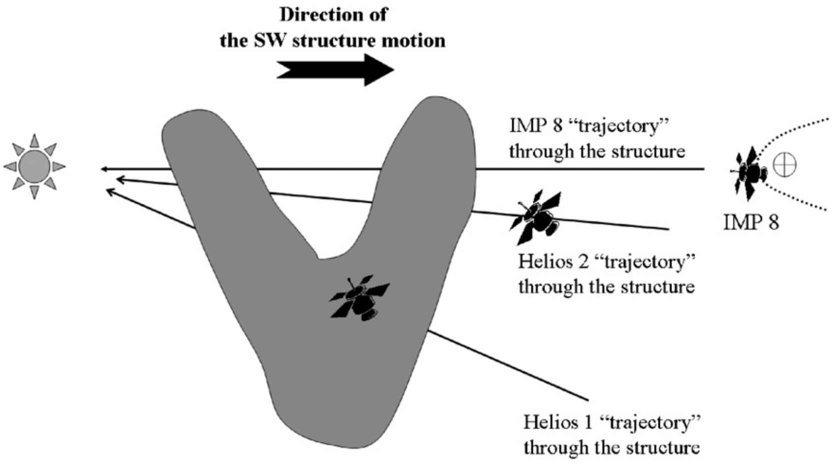

Fig. 4. Scheme of the pulse structure in the solar wind in the V-like shape explaining the hypothesis 2 (see the text).

Table 1
The main characteristics of the leading and trailing edges of the analyzed plasma density pulse seen by three spacecraft

	Δt_{lead}	ΔN_{lead} (%)	ΔB_{lead} (%)	$\Delta t_{\mathrm{trail}}$	$\Delta N_{\mathrm{trail}}$ (%)	$\Delta B_{\mathrm{trail}}$
Helios 1	8 min 6 s	44	−32	2 min 40 s	−73	26%
Helios 2	52 min 39 s	47	−18	6 min 40 s	−50	No data
IMP 8	13 min	71	−25	5 min	−47	30%

plasma density distribution in the direction perpendicular to the ecliptic plane.

Spatial inhomogeneities in the solar wind plasma can readily explain the discrepancy in behavior of the solar wind density between Helios 1, 2 and IMP 8. Definitely, at the leading edge of the plasma pulse, the Helios 1, 2 probes are separated from IMP 8 along the Y-axis by 7×10^6 and 5×10^6 km, respectively, and at the trailing edge, these separation distances decreased to 4.8×10^6 and 4×10^6 km. We see that this separation distance is large enough to be a reason for the different plasma behavior seen by these spacecraft. It is interesting to note that the separation distances between the spacecraft during the studied event perfectly match the averaged correlation length along the Y-axis direction of the solar wind plasma (800 radii of Earth or about 5×10^6 km) found by Dalin et al. (2002b). Of course, this may be just a coincidence but we cannot reject a possibility that there is a characteristic spatial scale of about 5×10^6 km in the solar wind plasma.

3.3. Inclination of the sharp plasma boundaries

Under this hypothesis, one must assume that there is an inclination of the plane of the plasma front relative to the direction of the bulk velocity of the solar wind. According to paper of Riazantseva et al. (2003b), we can check this assumption in the following way. The angle α between the normal to the plane of the plasma front and the direction of the solar wind flow is estimated as: $\mathrm{tg}(\alpha) = \Delta t \times V_0/\Delta Y$, where Δt is the additional time shift, V_0 is the average solar wind speed and $\mathit{\Delta Y}$ is the separation distance between the spacecraft along the Y-axis. For the Helios 1 and 2 pair, the delay in registration of the trailing edge is only 3 min. Having the average solar wind speed of 450 ± 20 km/s and the separation distance of 0.8×10^6 km, it gives the angle $\alpha_{\mathrm{H1,H2}} = 5.8 \pm 0.5^\circ$.

An additional time shift between the trailing edge seen by Helios 2 and IMP 8 is 12 h and the separation distance is equal to 3.9×10^6 km. This yields $\alpha_{\mathrm{H2,IMP8}} = 78.7 \pm 0.5^\circ$. Thus, it seems that we have obtained a direct contradiction between two estimates (5.8° versus 78.7°) of the front inclination. Thus, this idea has a low probability and the additional time delay of 12 h between Helios 2 and IMP 8 should be explained by large spatial inhomogeneities of the front pulse (like a step) in the direction perpendicular to its motion.

4. Stability of the sharp edges of the large plasma pulse

Table 1 represents the main parameters of the leading and trailing edges of the analyzed plasma density pulse by observations of three spacecraft. In Table 1 and Fig. 3a one can see that the gradient of the leading edge becomes weaker during its motion from Helios 1 to 2. The duration of the leading edge increases from 8 min to about 1 h, whereas the value of the jump remains at the same level. If one assumes that the leading edge is observed at 16:00 UT in the IMP 8 data, then the duration of its sharpest part is 13 min only with the 71% increasing density. In this case, this sharp front has survived rather well over a distance of 0.6 AU (90×10^6 km). On the other hand, a very sharp trailing edge (several minutes) approximately maintains its shape and amplitude during the 11.3 h of its motion between Helios 1 and 2. Moreover, this edge is seen to be very stable as it moves from Helios 2 to IMP 8 over 55.6 h, with ramp-durations of about 7 and 5 min, respectively.

Summarizing, the trailing edge remains very stable on the path from Helios 1 to the Earth, i.e., at distances more than half of the distance between the Sun and Earth. This result (conservation of the sharp boundary over a long distance) qualitatively agrees with the same conclusion found by Zastenker et al. (2006) but the latter was obtained only for the distance about 10^6 km, i.e., about two orders of magnitude less than the distance estimated in the present paper.

5. Conclusions

We have analyzed the large plasma density pulse observed by the Helios 1, 2 probes on April 1–2, 1977 and by the IMP 8 satellite on April 3–4, 1977. Based on the detailed comparison of the solar wind parameters at three different distances from the Sun, we can summarize our results as follows:

(1) For the first time it is shown that a very sharp edge (with duration of several minutes) of the solar wind plasma density pulse remained very stable during its motion for as long as 2.3 days or over distance of 0.6 AU (90×10^6 km), i.e., more than half of the distance between the Sun and Earth. Therefore, sharp edges of plasma structures might survive over larger distances, perhaps over the entire pass from the Sun to Earth.

(2) The area of a high plasma density (by 50% above the undisturbed solar wind density) extended approximately 22×10^6 km along the Sun–Earth line and had the similar outer boundaries over a distance at least of 2×10^6 km in the Y-direction.

(3) Using these observations, we have obtained that the plasma density distribution inside the plasma pulse structure evolved during its motion between Helios 1 and 2 separated along the X-axis by 18×10^6 km or by 11–12 h of the solar wind's motion. Thus, one maximum of the high plasma density was divided into two parts in such a way that these two structures moved in opposite directions relative to the background stream. This results in an expansion of the leading edge of the plasma structure. On the other hand, this apparent evolution may be readily explained by the spatial inhomogeneities in the solar wind plasma due to the difference in spatial locations of the two probes along the Y-axis.

A search for other similar prominent events based on Helios data will be continued in order to investigate the dynamics of sharp edges of structures under different physical conditions in the solar wind.

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