THE "AVERAGE" SOLAR WIND IN THE INNER HELIOSPHERE: STRUCTURES AND SLOW VARIATIONS.

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Abstract

Measurements from the HELIOS solar probes have indicated that apart from solar activity related disturbances there exist two states of the solar wind which might result from basic differences in the acceleration process: the "fast" solar wind ($v > 600$ kms^{-1}) emanating from magnetically open regions in the solar corona and the "slow" solar wind ($v < 400$ kms^{-1}) correlated with the more active regions and its mainly closed magnetic structures. In a comprehensive study using all HELIOS data taken between 1974 and 1982 we analyzed the "average" behavior of the basic plasma parameters as functions of the solar wind speed. We found that some quantities (e.g. momentum flux, total energy flux) are remarkably independent of the speed, others (e.g. particle density, enthalpy flux, angular momentum flux, α-particle to proton ratio) are not. The long term variations of the solar wind parameters along the solar cycle were also determined and numerical estimates given. These modulations appear to be distinct though only minor. In agreement with earlier studies we conclude that the major modulations are in the number and size of high speed streams and in the number of interplanetary shock waves caused by coronal transients. The latter ones usually cause huge deviations from the averages of all parameters. It is demonstrated that, apart from those solar activity related cases, even the "normal" acceleration mechanisms of the solar wind may occasionally become dramatically changed in such a way that large areas of the corona emit low density low speed plasma with a critical point beyond 0.3 AU. The occurrence of such strange excursions may put new constraints on any theory of solar wind expansion.

I. Introduction

Asking for the average solar wind might appear as silly as asking for the taste of an average drink. What is the average between wine and beer? Obviously mere mixing - and averaging means mixing - does not lead to a meaningful result. Better taste and judge separately and then compare, if you wish. After a while you will have developed a set of criteria for differentiating. Then you may eventually come from analysis to synthesis: You really can appreciate what you are drinking. So much for the drinks.

The trouble with the solar wind is more difficult: We do not know the significant criteria to begin with. For a long time the theorists have thought in terms of a "quiet" wind and believed to find it represented in the "slow" wind (for references, see Hundhausen, 1972). This is easily understood since the experimentally determined numbers for the slow wind fitted the available theoretical models much better, and they still do. It wasn't until Feldman et al. (1976) suggested that if there is a "quiet" wind at all it is more likely to be found in the "fast" wind, i.e. in the high speed streams occurring predominantly a few years before sunspot minimum. During the Skylab era in 1973/74 we learned that these high speed streams emerge from coronal holes (Hundhausen, 1977 and references therein). The unique association between these two phenomena has since then been well established and was found to be valid even in detail (Burlaga et al., 1978). Not only do the Skylab X-ray pictures of coronal holes show surprisingly sharp edges (Bohlin, 1977, and references therein), it was also found that the high speed streams are surrounded by comparatively thin boundary layers separating them from the adjacent slow solar wind. This became especially clear when HELIOS 1 approached the sun for the first time in early 1975 (perihelion at 0.31 AU): there the interaction region between stationary corotating high speed streams and the slow plasma ahead can be as "thin" as 2° in solar longitude (Schwenn el al., 1976). A similar number was found for the latitudinal boundaries of high speed streams (Montgomery, 1976, Schwenn et al., 1978). It must now be regarded as normal that two spacecraft moving close to the heliocentric equator but separated in heliocentric latitude by not more than 10° observe completely different stream structures in most cases. They can even move on different sides of the interplanetary current sheet, i.e. in opposite magnetic sectors. This was demonstrated in early 1976 when the two HELIOS probes at a latitudinal separation of 12° were travelling in opposite magnetic sectors for about a quarter of a solar rotation (Schwenn et al., 1977, Burlaga et al., 1981).

Based on all these results one is tempted to assume almost rectangular flow speed profiles close to the sun (Gosling et al., 1978) which resemble very closely those of the underlying coronal holes. Slow solar wind and high speed streams might be essentially different phenomena and might result from different acceleration mechanisms in the corona (as suggested by Rosenbauer et al., 1977, Schwenn et al., 1981a, b).

There have been attempts to explain the strange "switching" between the two states in terms of multiple critical points which may occur when the divergence of open magnetic field lines, e.g. in coronal holes, exceeds certain limits (Kopp and Holzer, 1976, Holzer, 1977). Unfortunately, there is still no conclusive answer to such basic questions, as what accelerates the fast solar wind to its high speed, what causes the sharp boundaries, and where the slow solar wind really comes from.

From the foregoing remarks it seems reasonable that one criterion for sorting the solar wind into different categories should be the bulk speed. In the second part of this paper I will apply this criterion to all the HELIOS solar wind data taken between 1974 and 1982 and discuss the "average" parameters as functions of the bulk speed. The effects of undesired "mixing" caused by solar activity related disturbances will be considered. In the third part I will show if and how the basic "average" solar wind parameters change during the solar cycle. At the end of the discussion I will mention a few exceptional excursions which obviously do not fit into any of these categories.

II. Long term averages

1. The method

For this comprehensive analysis we took all data from the plasma experiment on both HELIOS solar probes (Schwenn et al., 1975). HELIOS 1 had been launched on Dec. 10, 1974 into a highly elliptic heliocentric orbit with a perihelion distance of 0.3 AU. HELIOS 2 followed on January 15, 1976 and approaches the sun as close as 0.29 AU. The orbital period is 190 days for HELIOS 1 and 186 days for for HELIOS 2. For further details see Porsche (1977). The plasma data were evaluated by a one-dimensional method briefly described by Rosenbauer et al. (1977). The proton densities were normalized to 1 AU assuming a r^{-2} dependence. All data were used on the basis of individual spectra and no averages were performed beforehand. (Just for comparison we calculated 1 hr averages and used those as inputs for the final analysis. Although the results did not change significantly we feel that this latter method is not appropriate: During many hours there were just single data points, the unavoidable scatter of which gained too much weight by this kind of averaging). The HELIOS 1 data set covered the time period from Dec. 12, 1974 to Feb. 28, 1982 resulting in 1,602,231 total spectra. The HELIOS 2 data cover the time span from Jan. 17, 1976 to Mar. 8, 1980 including 913,142 total spectra. We grouped the data in seven speed classes (< 300; 300 - 400; 400 - 500; 500 - 600; 600 - 700; 700 - 800; > 800 kms^{-1}) and calculated the relevant average parameters within these classes. The bottom panel in Figure 1 shows how the data are distributed over the classes. Within each speed class we sorted the data into radial bins of 0.02 AU width according to the radial distance at which they had been measured. By this technique we were also able to determine radial trends.

2. Average proton parameters

Figure 1 tells us how the proton density n_p, the flux density $n_p\, v_p$ and the momentum flux density $n_p\, m_p\, v_p^2$ depend on the bulk speed. We notice some systematic smooth trends for all these quantities as functions of v_p. Only the group $v_p > 800\ \mathrm{kms}^{-1}$ shows marked deviations. A closer inspection of the data contributing to this particular group reveals that most of them are due to fast plasma accelerated by shocks associated with increasing solar activity from 1977 on. In order to find the impact of such transient phenomena on our data set we did a similar analysis with a subset of data (445,571 from HELIOS 1 and 238,923 from HELIOS 2) taken before 1977. Data associated with major shocks occurring even before that date were also excluded. The result in Figure 2 shows that the trends are now more distinct. It turns out that the particle flux $n_p\, v_p$ and even more dramatically the normalized density decreases steadily with increasing speed. On the other hand, the momentum flux is remarkably equal for all speed classes.

The average quantities might be affected by stream-stream interactions as well. We did not study this here since the influence can be expected to be only minor inside 1 AU (Goldstein and Jokipii, 1977). The width of these interactions regions is small compared to the streams themselves (see, e.g., Figure 1 in Rosenbauer et al., 1977) and gets even smaller at decreasing distances from the sun.

3. Average energy flux

In Figures 3 and 4 we find similar histograms for the energy flux density. The kinetic energy flux $n_p\, v_p\, (1/2\ m_p\, v_p^2)$ shows a marked increase with speed, which is due to its dependence on v_p^3. On the other hand, the gravitational energy flux $n_p\, v_p\, (G\, m_p\, M_\odot/R_\odot)$ which stands for the work required to overcome

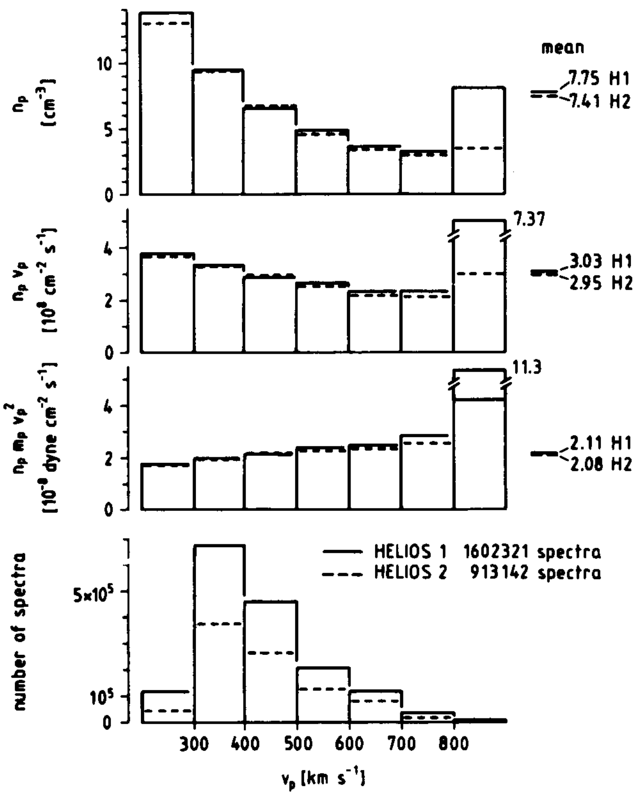

Figure 1 Average values of the solar wind proton density n_p, the proton flux density $n_p v_p$, and the proton momentum flux density $n_p m_p v_p^2$, as functions of the flow speed. The bottom panel shows the number of points in each speed class. All data from both HELIOS solar probes taken between Dec. 12, 1974 and Feb. 28, 1980 are included.

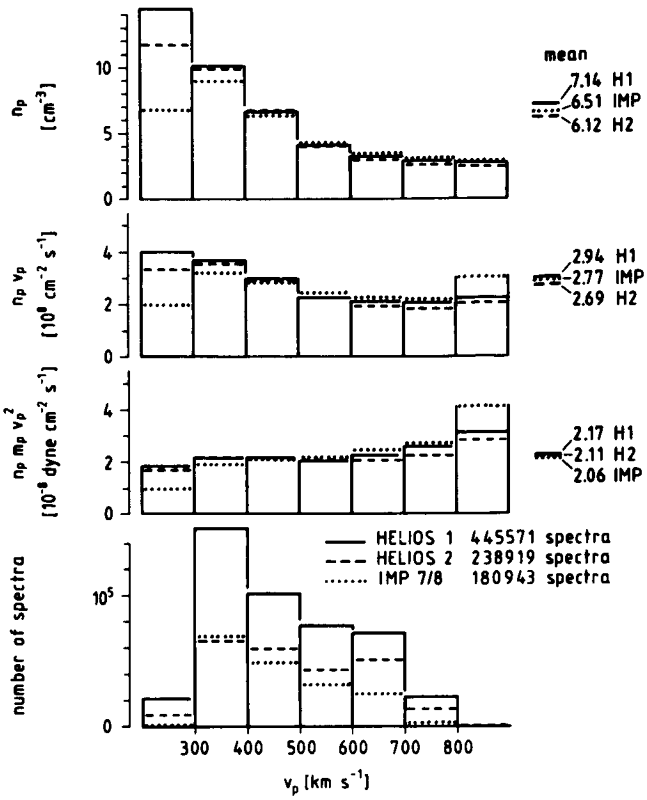

Figure 2 Same as Figure 1, but the data from 1977 on and some other shock disturbed data before 1977 were excluded. The IMP7/8 data were kindly provided by the Los Alamos group.

solar gravity goes only linearly with v_p and is therefore proportional to the particle flux n_p v_p. The enthalpy flux n_p v_p (5/2 kT_p) does not add more than ∿ 3 % to the total energy flux, nor does any other energy flux such as proton and electron heat fluxes and the Alfvén wave energy flux (Denskat, 1982). Adding up all these components we find the flux density of the total energy, i.e. that energy the sun is losing by releasing the solar wind plasma, to be remarkably independent of v_p. This is even more evident from Figure 4 which is again based on HELIOS data before 1977 only.

We checked these results with plasma data obtained at 1 AU from the earth-orbiting IMP7/8 satellites (kindly supplied to us by the Los Alamos group direc-

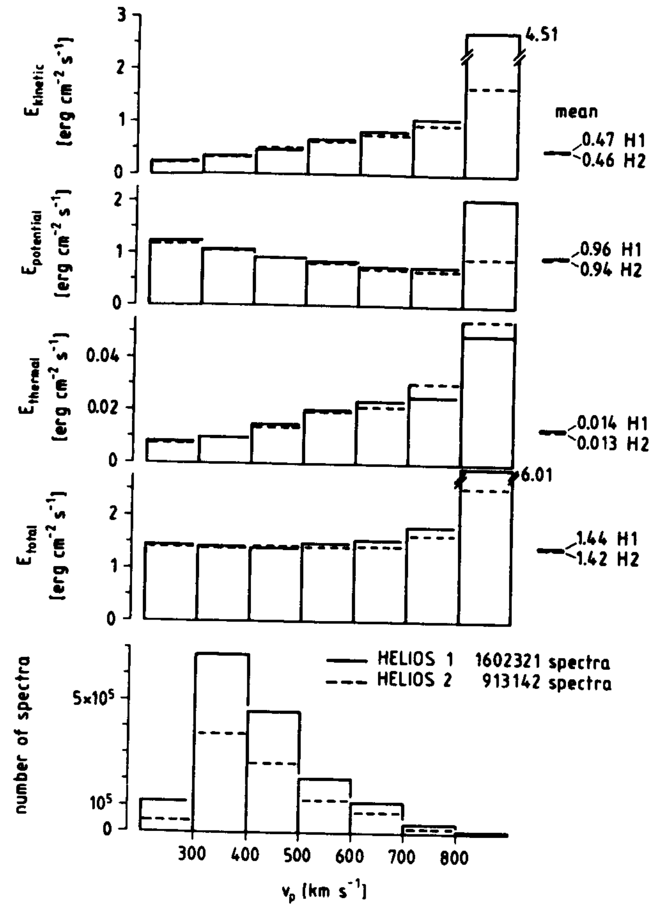

Figure 3 The average solar wind energy flux density, derived from the same data as in Figure 1.

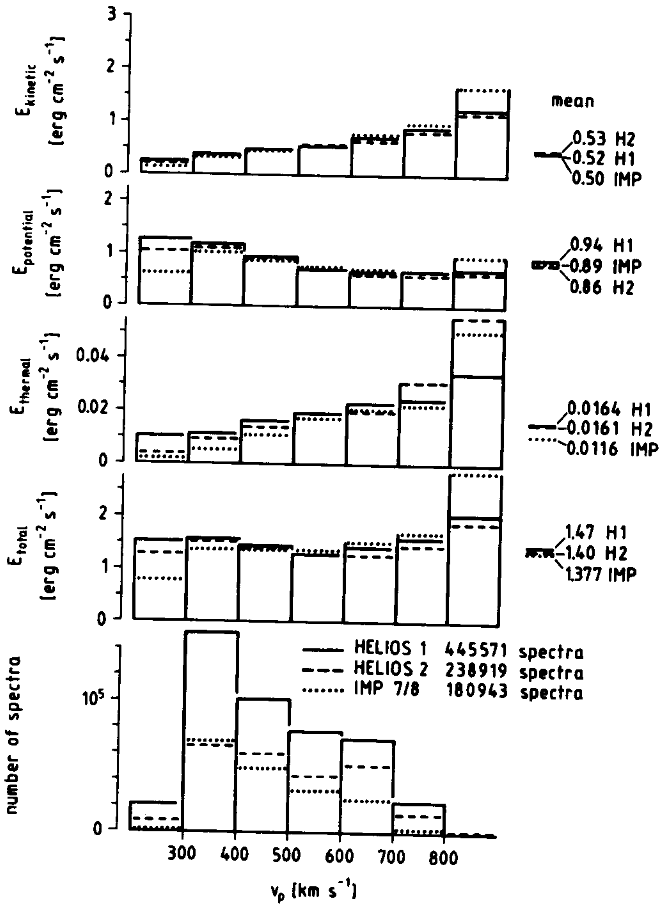

Figure 4 The average solar wind energy flux density, derived from the same data as in Figure 2.

ted by Dr. Sam Bame. Intercalibration between the IMP and HELIOS spacecraft was performed using the data of the first few days after the launches of HELIOS 1 and HELIOS 2, respectively. This led to a correction factor for the IMP proton densities of 0.70). These data, taken between Dec. 12, 1974 and Dec. 31, 1976, show exactly the same trends (see Figures 2 and 4).

We tried to find out the cause for the slightly different trends of the averages in the $v_p > 800$ kms^{-1} class. It turned out that, e.g., in case of HELIOS 2 there were 1077 points in this class (before 1977), 1067 of which stem from one single high speed streams in April 1976 observed at 0.3 AU (see Marsch et al., 1982a, b). In Figure 16 of the paper by Marsch et al. (1982a) we find a time plot of these particular data. We see that in this period v_p is only some 700 kms^{-1} on the average. Values of up to 900 kms^{-1} are reached occasionally in the form of rather sharp peaks, due to strong Alfvénic turbulence. Depending on the instantaneous orientation of the magnetic field the proton speed can reach extreme values while the density remains constant. Because of our procedure these extrema were grouped in a separate class. This grouping causes the large values of all average quantities involving any power of v_p. By first calculating, e.g., 1 hr averages of these parameters and then sorting those according to the speed classes, we found that now both the momentum flux and the total energy flux are constant within ± 10 % of the average flux regardless of the proton bulk speed. Similar arguments also hold for HELIOS 1 and IMP where the total number of points in the class $v_p > 800$ kms^{-1} is even less (466 and 13, respectively).

4. Average radial gradient of the proton temperature

The radial gradients of the proton temperature T_p are displayed in Figures 5 (all data) and 6 (data before 1977). For this purpose we fitted the radial dependence of T_p within each speed class by an $r^{-\gamma}$ law. We find that for slow speeds γ

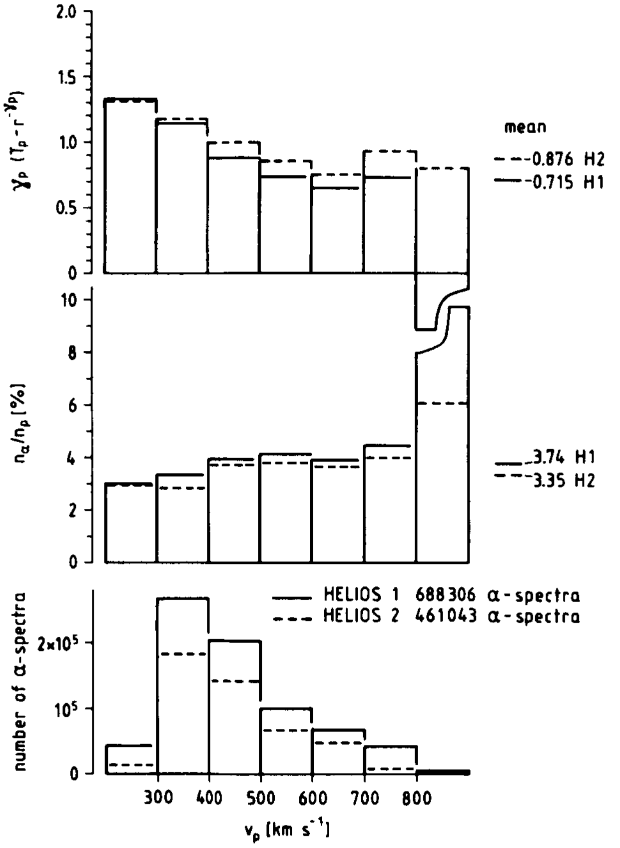

Figure 5 The average proton temperature radial gradient index γ_p (assuming a $r^{-\gamma}$ dependence) and the average α-particle abundance n_α/n_p, derived from the same data as in Figure 1. For n_α/n_p only those data were used, where HELIOS was outside 0.5 AU.

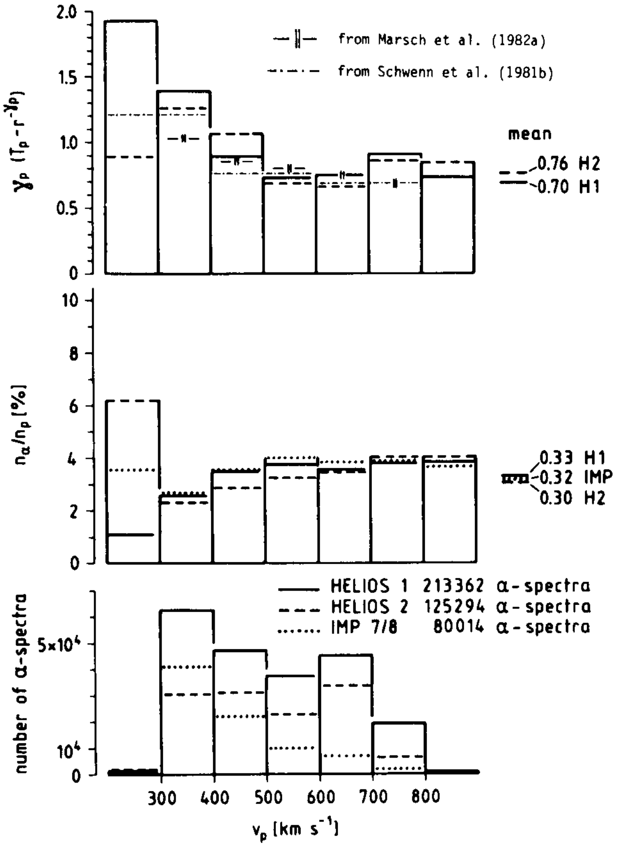

Figure 6 Same as Figure 5, but with the same limited data set as in Figure 2.

is close to the adiabatic value of $\gamma = 4/3$. For higher speeds γ is significantly lower. The numbers are in good agreement with those determined by Schwenn et al. (1981b) from radial line-ups between HELIOS 1 and HELIOS 2 and those for $T_{\parallel}$ calculated by Marsch et al. (1982a) from evaluations of the 3D-velocity distribution (one must be aware that T_p as used for this analysis results from a projection of the velocity distribution onto the radial direction and a succeeding 1D evaluation. $T_{\parallel}$ is the second moment of the distribution function parallel to the local magnetic field. Thus T_p can be expected to be equal to $T_{\parallel}$ only if the magnetic field is radial).

5. Average α-particle abundance

The second panels in Figures 5 and 6 show the α-particle abundance (relative to protons) n_α/n_p. For this part of the analysis we used data only from periods in which the HELIOS probes were outside 0.5 AU in order to avoid possible confusion with fast streaming proton components often found inside 0.5 AU (Marsch et al., 1982b). There can be no doubt about a slight but definite dependence on v_p, especially in the undisturbed data taken before 1977 (Fig. 6). The large scatter of n_α/n_p in the speed class $v < 300$ kms^{-1} is certainly a small-sample effect. The fast solar wind contains ∿ 3,6 % α-particles, the slow plasma only ∿ 2,5 % (Note that the n_α/n_p ratio tends to be too large, since spectra with too few α-particles had to be excluded from this analysis. Such α-particles depletions occur mainly in the slow solar wind. That means that the real α-abundance difference between slow and fast solar wind could be even more pronounced). Our data are also consistent with a result reported by Borrini et al. (1981). They had found significant depletions in n_α/n_p around magnetic sector boundaries which are normally imbedded in slow solar wind.

This abundance difference might be regarded as indicator of a qualitative difference in the coronal sources of both types of solar wind flow.

6. Average angular momentum flux

Now we regard the angular momentum flux $n_p m_p r v_{pr} v_{p\varphi}$ transported by the solar wind. In an extensive study recently published by Pizzo et al. (1982) it was found (among other important results) that it is the slow solar wind only that takes away positive angular momentum (in the sense of corotation) from the sun. The fast wind carries nearly no angular momentum at 0.3 AU. (Because of stream-stream interactions the momentum flux obtained from averaging all data between 0.3 and 1 AU reaches even a negative value, see Table 2.) The measurements indicate clearly, that this basic difference between slow and fast flow is of solar origin. This appears to be a very important observation since it might mean that the slow plasma is released at a significantly larger Alfvén radius than the fast plasma. This is another additional hint that there are possibly differences in the acceleration mechanisms for slow and fast solar wind (Kopp and Holzer, 1976).

7. Other radial gradients

In a further step we investigated the radial dependence of the solar wind parameters. For simplicity we assumed linear functions with r (except for the temperature which has been discussed already) and performed least square fits. The averages within the radial bins were weighted according to the number of data points included. In Table 1 the average changes between 0.3 AU and 1 AU (in per cent) determined by this procedure are listed.

	HELIOS 1		HELIOS 2	
	all	before 77	all	before 77
v_p	11.0	17.4	4.4	5.7
n_p	-18.1	-22.6	-10.1	- 6.3
$n_p v_p$	- 2.8	- 5.6	10.0	3.3
$n_p m_p v_p^2$	12.7	12.6	10.6	12.4
E_{Kin}	28.7	30.9	17.6	18.8
E_{pot}	- 2.8	- 5.6	10.0	3.3
E_{total}	4.9	5.0	5.5	7.5

Table 1 Radial variations of average solar wind parameters between 0.3 AU and 1 AU, in per cent. The proton density n_p has been normalized to 1 AU assuming a r^{-2} dependence.

The table shows that it is the particle flux $n_p v_p$ that appears to be about constant. This indicates that on the average there is no significant meridional flow out of or into the plane of the ecliptic, to which our measurements are restricted. Owing to a general increase of the flow speed during the radial expansion (mainly in the slow plasma, Schwenn et al., 1981b), the average proton density n_p drops by a few per cent faster than according to a r^{-2} law. The increase in the bulk speed leads to even stronger increases in the flux densities of proton momentum and kinetic energy. The total energy flux in the protons grows by about 5 % between 0.3 and 1 AU. There are only two main energy sources that may supply this energy. Protons could gain

1. the α-particle kinetic energy which at least in high speed streams drops from ≈23 % to ≈17 % of the proton kinetic energy, due to the decreasing differential speed (Marsch et al., 1982b), and
2. the Alfvên wave energy flux which at times of Alfvênic turbulence drops from 5 % to 2 % of the total energy flux (Denskat, 1982).

However, the mechanism of this energy transfer, probably through some wave particle interactions, still awaits explanation.

8. Average solar wind around sunspot minimum

In Table 2 the average values of the basic parameters for the time between Dec. 12, 1974 and Dec. 31, 1976 are summarized, this time with only two subgroups for "slow" ($v_p < 400$ kms^{-1}) and "fast" ($v_p > 600$ kms^{-1}) solar wind. Our numbers agree reasonably well with those given by other authors (e.g., Hundhausen, 1972, Feldman et al., 1977, Schwenn, 1981). However, detailed comparisons would require extensive discussions of the differences in the evaluations (instrument techniques, calibrations, data evaluation, selection criteria, status of the solar cycle etc.) and would go beyond the scope of this paper.

		$v_p < 400$ kms^{-1}	$v_p > 600$ kms^{-1}	all data
v_p	kms^{-1}	348	667	481
n_p	cm^{-3}	10.7	3.0	6.8
$n_p v_p$	cm^{-2}s^{-1}	3.66×10^8	1.99×10^8	2.86×10^8
$n_p m_p v_p^2$	dyne cm^{-2}	2.12×10^{-8}	2.26×10^{-8}	2.15×10^{-8}
E_{kin}	erg cm^{-2}s^{-1}	0.37	0.76	0.52
$E_{grav.}$		1.17	0.65	0.91
$E_{Enth.}$		0.011	0.023	0.016
E_{total}		1.55	1.43	1.45
n_α/n_p	%	2.5	3.6	3.2
$n_p m_p r v_{pr} v_{p\varphi}$	dyne cm sterad^{-1}	1×10^{30}	-0.7×10^{30}	0.4×10^{30}
γ	from $T_p \sim r^{-\gamma}$	1.2	0.7	-

Table 2 Average solar wind parameters for the time between Dec. 12, 1974 and Dec. 31, 1976. The proton density n_p has been normalized to 1 AU assuming a r^{-2} dependence.

9. Summary on long term averages

The most important results and conclusions of this first part of the analysis can be summarized as follows:

1. The parameters most sensitive to the bulk speed are the proton density and the angular momentum flux, as well as the particle flux, the α-particle abundance, the proton temperature and its radial gradient.
2. At times of low solar activity the momentum flux and the total energy flux are remarkably insensitive to the bulk speed.
3. The differences in angular momentum flux as well as the α-particle content indicate different release heights in the corona for fast and slow solar wind.

4. The particle flux density does not change between 0.3 AU and 1 AU, i.e. on the average the solar wind flow in the ecliptic is purely radial.
5. The net gain of proton kinetic energy between 0.3 AU and 1 AU requires some energy transfer still to be explained.
6. The relative insignificance of the Alfvên wave energy flux as well as the lack of speed dependence of the fluxes of total energy and momentum might conceal some clues to understanding the solar wind acceleration mechanisms.

III. Slow variations during the solar cycle

1. Solar wind stream structure

The possible modulation of the solar wind during the solar activity cycle has always been a subject of great interest, which is reflected in a number of papers at this conference (see also Hundhausen, 1979 and references therein).

One quantity that is apparently directly related with the solar activity cycle is the occurrence rate of interplanetary disturbances, such as shock waves. I will not discuss this correlation any further except for the impact these disturbances might have on the long term averages.

Bame et al. (1976) pointed out that a significant modulation is also evident in the number, size and amplitude of high speed streams. Figure 7 reproduces the original figure published by Bame et al. (1976), with a few points added. These points have been determined from HELIOS data using the same criteria as were used in the original work. The most prominent feature in Figure 7 is the appearance of large stable high speed streams in the last third of the past sunspot cycle about two years before activity minimum. This caused a simultaneous peak in the average solar wind bulk speed ($\sim$ 550 kms^{-1}) compared to minimum values of $\sim$ 430 kms^{-1} (Feldman et al., 1978). Extrapolating this data set, which already covers more than 11 years, we would expect the next appearance of stable high speed streams not later than by the end of 1983. There is a fair chance that HELIOS 1 might survive until then.

2. Modulation of proton parameters

It has been found that the modulation of the average solar wind, if there is one at all, is only minor compared to intercalibration uncertainties between several instruments on several spacecraft usually required for such a long term study. This is especially true for all those solar wind parameters involving particle densities.

The HELIOS data offer a unique opportunity for a quite comprehensive analysis. This data set is rather "complete" throughout the whole time span of seven years and three months, up to now. It covers for the first time all significant parts of a solar activity cycle: end of the declining phase, activity minimum, activity increase and maximum, beginning of the declining phase. Furthermore, there was no degradation or change in the instruments' performance. This was checked by extensive inflight tests and by cross calibrations between the two completely independent but simultaneously measuring instruments. The wave experi-

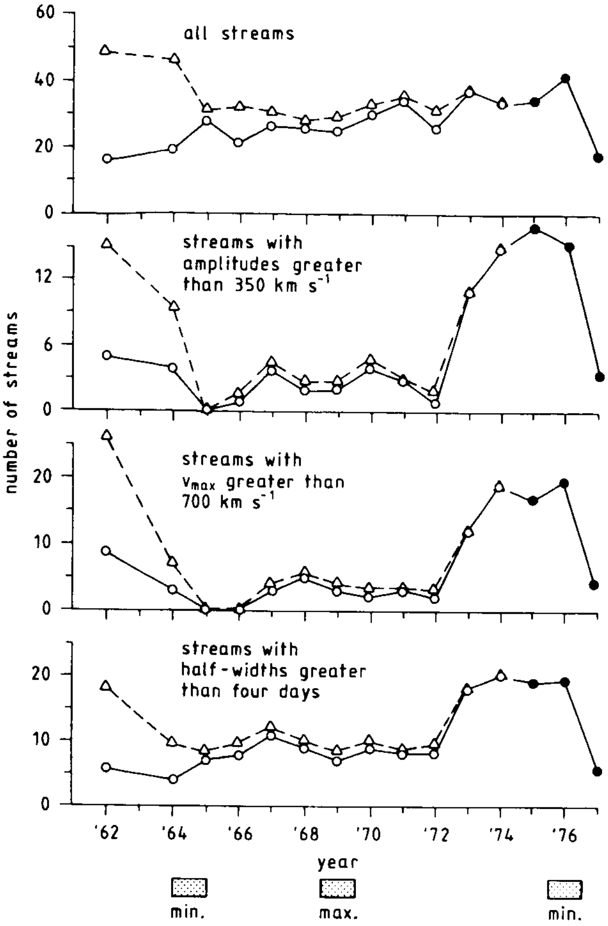

Figure 7 Yearly numbers of all solar wind streams with amplitudes greater than 150 kms^{-1}, with amplitudes greater than 350 kms^{-1}, with maximum speeds greater than 700 kms^{-1}, and with half-widths greater than 4 days (from top to bottom). The solid dots denote the numbers observed directly; the triangles denote extrapolated estimates for complete data coverage. From Bame et al. (1976).

The solid dots were determined from HELIOS data using the same criteria as in the original work.

ments on board the HELIOS probes measured the electron plasma frequency $f_e = (n_e e^2/\pi m_e)^{1/2}$ in several cases of strong plasma oscillations (Gurnett and Anderson, 1977, Kellogg, private communication, 1976) and confirmed our absolute density calibration within only 20 % uncertainty.

The data points shown in the next few figures are in each figure averages of the relevant parameters through one complete solar rotation. Again we used as input data the individual spectra. No single data point has been omitted. The number of individual points for each rotation average is shown in the bottom panels of Figure 8. The proton densities have been normalized to 1 AU, as before.

In Figure 8 we see the behavior of the proton bulk speed, density, particle and total energy flux densities. The shaded lines are supposed to show what we think are long term trends:

1. There is a definite decrease in v_p from ∿ 550 in early 1975 to ∿ 370 kms^{-1} in 1980 with a slight indication of an increase in 1981/82.
2. n_p is modulated by ± 10 % of the average value with a maximum in 1977 and a minimum at the end of 1979.
3. The particle flux shows a similar modulation with an amplitude of ∿ ± 15 % of average.
4. The total energy flux shows a similar modulation; the maximum is not so well pronounced, but the minimum in early 1980 is by 20 % lower. The increase from 1980 to 1982 is rather steep.

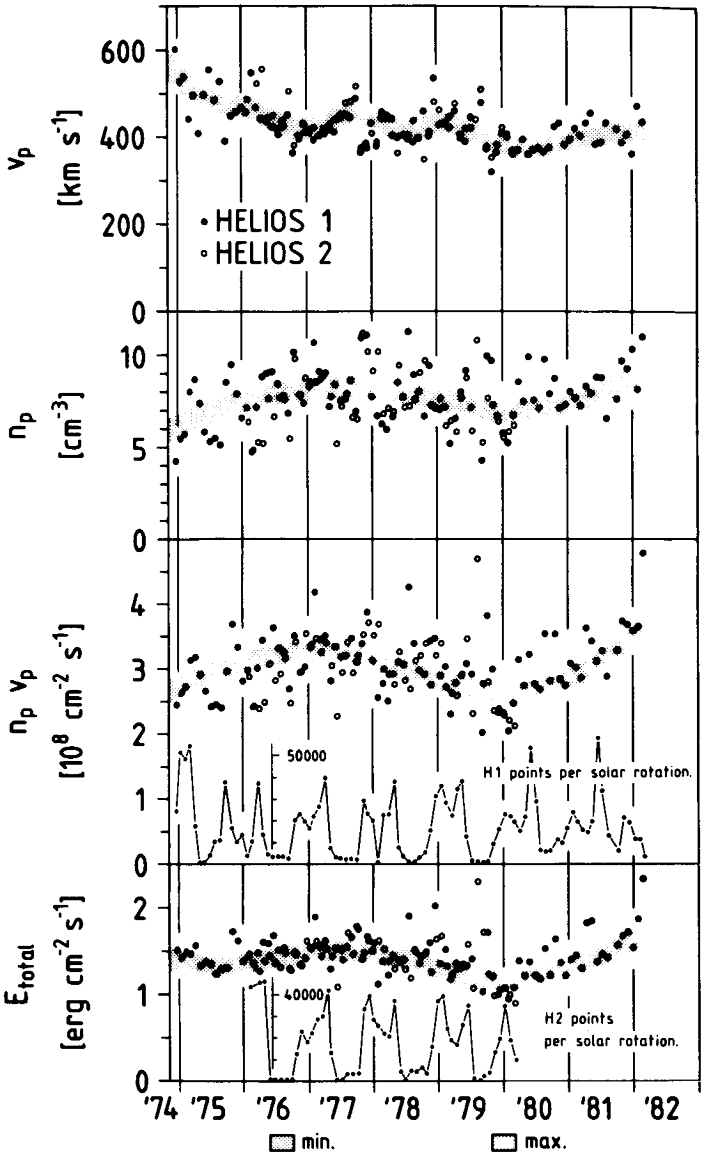

Figure 8 The variation of proton flow speed v_p, density n_p, flux density n_pv_p and total energy flux density from 1974 to 1982, based on all HELIOS data. Each point represents an average value during one complete solar rotation. The number of points per rotation is indicated in the two lower panels.

5. For the fluxes of particles and total energy one might be inclined to see an overall upward trend superimposed on a sinusoidal modulation.
6. The increasing number of solar transients from 1977 on which caused so many shockwaves (up to some 20 per solar rotation) did not at all influence the averages. Even the scatter of the solar rotation averages remained about equal throughout the solar cycle.

In an additional approach we sorted these data with respect to the heliocentric latitude at which they were measured. The result was not surprising. It reflects in all details the fact that a few years before sunspot minimum the high speed streams were faster and broader if they were associated with the south polar coronal hole. Hansen et al. (1976) had reported that the equatorial extension of the south polar hole had been significantly broader than its northern counterpart during 1973/74. This explains why Coles and Rickett (1976) found, based on interplanetary scintillation measurements of the solar wind speed at high latitudes, the yearly average speed to be remarkably higher at southern latitudes in those years. Our in situ measurements confirm that there was more high speed solar wind found at southern latitudes with all its typical features as mentioned above. This asymmetry weakened with rising solar activity and eventually disappeared altogether.

4. Modulation of α-particle abundance

The variation of the n_α/n_p ratio is presented in Figure 9. These data are again taken for $r > 0.5$ AU only. There is a clear trend evident in the data, with a definite minimum of ∿ 2.8 % around sunspot minimum in 1976. The big scatter in later years was caused by more and more transients associated with rising solar activity. The average flux of α-particles is obviously much more variable and sensitive to solar activity than that of the protons.

In Figure 10 we split up the data into three speed classes (slow, medium, fast), for two of which the results are shown here. We find, that n_α/n_p is lower in slow solar wind (see also Figure 5 and 6). We also see that the modulation along the sunspot cycle works mainly in the slow solar wind.

Generally, the recent HELIOS data confirm very well the trends published by Feldman et al. (1978). There appears to be a significant variation of n_α/n_p from the average value between 3 % at sunspot minimum and ∿ 4.5 % 3 years after sunspot maximum.

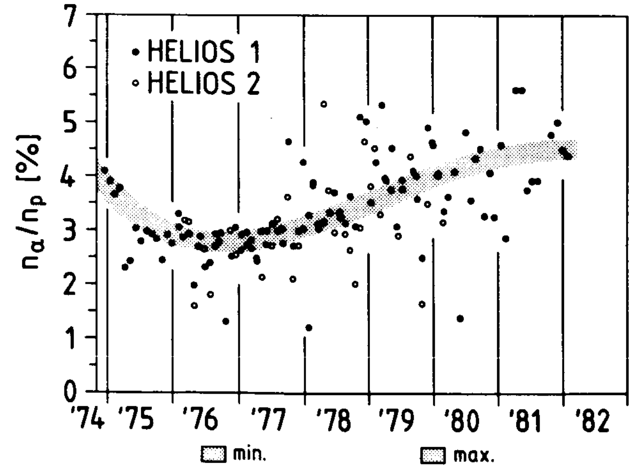

Figure 9 The variation of the α-particle abundance n_α/n_p from 1974 to 1982, based on all HELIOS data taken outside 0.5 AU.

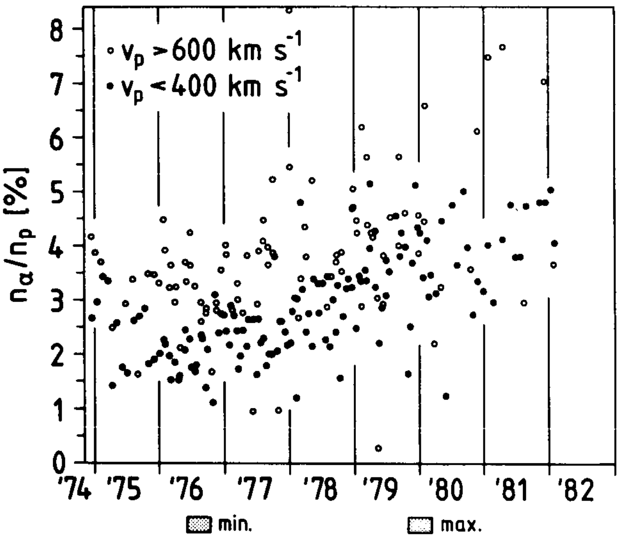

Figure 10 Same as in Figure 9, but only the data for $v_p < 400$ kms^{-1} and $v_p > 600$ kms^{-1} were selected and averaged separately.

IV. Exceptional excursions from the average

No rule without exceptions, no average without variances. There are enormous variances on all time scales in the solar wind (see, e.g., Hundhausen, 1972). The reason for finally abandoning the concept of a "quiet" solar wind is the simple fact that there never is a quiet solar wind. Especially the slow solar wind which can be traced back to the more active regions on the sun permanently shows fluctuations of all basic parameters. This holds as well for the times of low activity, when solar flares and other transients and their associated interplanetary disturbances are less frequent.

Occasionally there are unusual events observed in the solar wind which differ from all other phenomena in any respect chosen by which to compare them and which seemingly have no correspondence with any known solar event. Here I will present two examples of only one particular kind of those unusual events: The subalfvénic solar wind. In Figure 11 we see HELIOS 2 data taken from Nov. 9 to Nov. 16 in 1979 at 0.3 AU. The flow speed was generally low, around 300 kms^{-1}. On Nov. 13 the speed dropped further, below 200 kms^{-1}, and finally the peak of the proton velocity distribution went below our lowest E/q-channel (at 0.158 kV, i.e. 171 kms^{-1} for protons) for several hours. That was certainly the slowest solar wind ever reported. Because of the rather low plasma density ($\sim$ 20 cm^{-3}) and the high magnetic

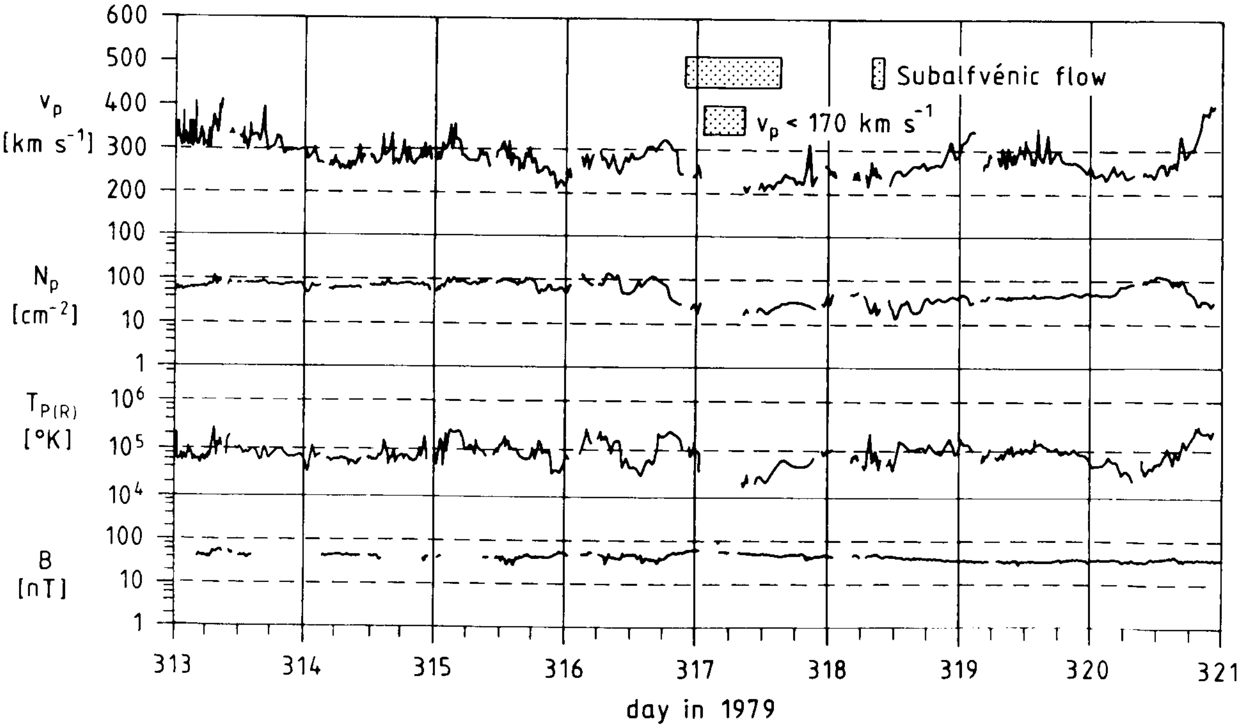

Figure 11 The subalfvénic solar wind flow on Nov. 13, 1979 as seen from HELIOS 2 at 0.3 AU. The magnetic field data were kindly provided by K.U. Denskat and F.M. Neubauer (TU Braunschweig).

field during that time the local Alfvén speed went as high as 300 kms^{-1} (the local proton sound speed was ∿ 15 kms^{-1}), i.e. nearly twice as much as the local plasma speed. In other words, the critical point for this particular plasma flow must have been outside 0.3 AU, if there was one at all. In very few cases have subalfvénic flows been observed recently in the piston gas driving strong flare-related interplanetary shocks (Richter, private communication, 1982). In this case, however, there was no shock involved within at least 4 days preceding the event nor was there any unusual coronal feature observed.

This event resembles somewhat another event observed by Gosling et al. (1982) at 1 AU on Nov. 22, 1979. Note that this is only 13 days after the HELIOS 2 event. Regarding the position of HELIOS 2 (100° east of the earth sun-line) and assuming a propagation time between 0.3 and 1 AU of a few days for this very slow solar wind we find it conclusive that both events were caused by the same solar source corotating stationarily. There are some differences in the details; HELIOS 2 found a very slow plasma speed at nearly normal densities, while IMP found a density depletion at normal speed. However, the main result is that in this case a sizeable part of the corona (some 10° of heliocentric longitude due to the event's duration at HELIOS 2, and 5.5° in latitude due to the separation between HELIOS 2 and IMP) could emit continuously for some 10 days very slow solar wind which remained subalfvénic until 0.3 AU and even 1 AU.

An even more dramatic event of a similar type was observed by HELIOS 1 on June 6 to 8, 1980 at a solar distance of 0.37 AU (Figure 12). Here the flow speed and the magnetic field remained about constant at 300 kms^{-1} and 35 nT, respective-

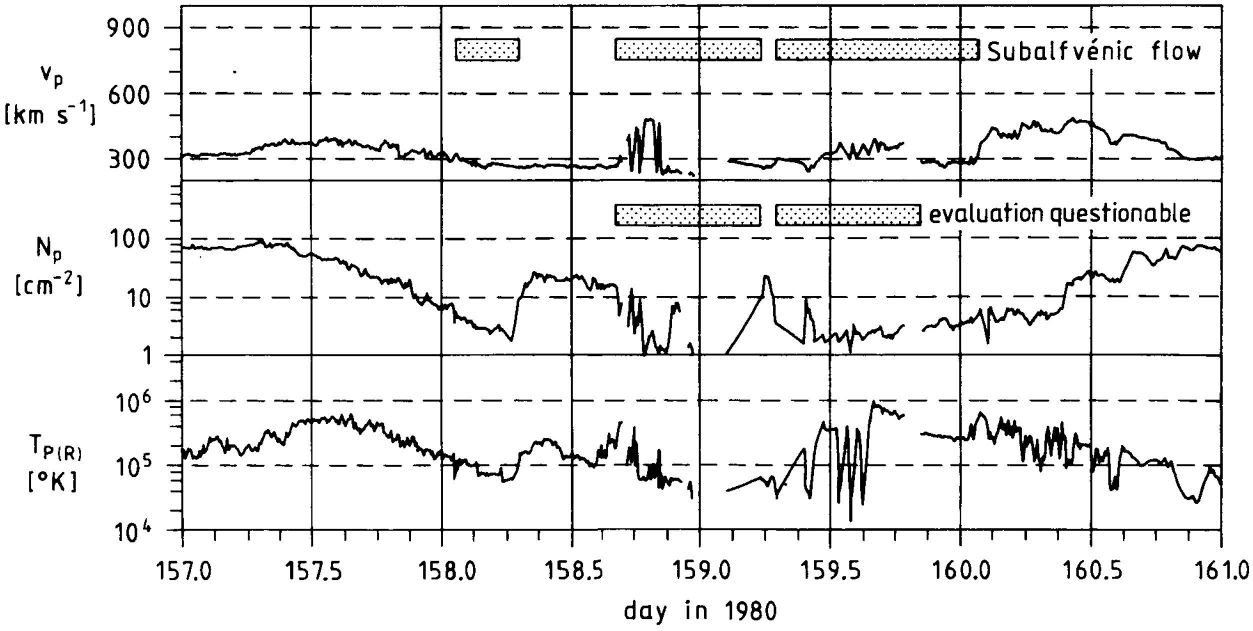

Figure 12 The subalfvénic solar wind flow on June 6 to 8, 1980, as seen by HELIOS 1 at 0.37 AU. During the intervals indicated in the Figure the data evaluation was questionable because of the extremely low particle densities, resulting in some abnormal values.

ly, but the density dropped to extremely low values. The density decreased steadily over an entire day from the normal value of $\sim$ 100 cm^{-3} to less that 1 cm^{-3}. The density was so low and the shape of the distribution function became so anomalous (very flat, up to 3 additional peaks at extreme speeds etc.) that a reasonable evaluation was no longer possible (We indicated the range of questionable data in Figure 12). Altogether, owing to this abnormal density "hole" in the solar wind the flow speed was subalfvénic for about two days, i.e. over about 20° in solar longitude, with only a few hours of interruption. Again, there was no disturbance in the interplanetary medium for several days ahead of the density drop, nor was there any associable solar feature seen.

In summary we have to conclude that the "normal" acceleration mechanisms of the solar wind eventually may become dramatically changed in such a way that large areas of the corona emit low density low speed solar wind with a critical point beyond 0.3 AU. The possibility of such strange though rare excursions from the average which are not related with any known solar phenomenon may put new constraints on any theory of solar wind expansion.

V. Concluding remarks

The properties of the "average" solar wind as described in this study were derived from some 2.5 million individual data points measured during a time span of more than seven years. We were well aware that averaging of data sets may produce problems resulting from unknown underlying mechanisms, as outlined in the introduction. It appears now that, after all, the choice of the solar wind flow speed as a basic parameter for sorting the data in different categories was a good one.

Our study increased the evidence for qualitative differences between high speed and low speed solar wind. In particular, the differences in angular momentum flux as well as the α-particle content indicate different release heights in the corona for fast and slow solar wind, confirming our earlier suggestion of differences in the acceleration process (Rosenbauer et al., 1977). However, other basic parameters such as the fluxes of momentum and total energy are surprisingly insensitive to the bulk speed, particularly if disturbed data (resulting from "mixing" by solar activity related transients) are excluded. In current theoretical models of solar wind acceleration these parameters are normally very sensitive to any variation in the boundary conditions (see, e.g., the paper by Leer, at this conference). Therefore the obvious lack of speed dependence in the actually observed parameters appears to be of particular significance.

The long term variations of the "average" solar wind were also determined. We confirm the result from earlier work (Bame et al., 1976) concerning the definite modulation of the number and size of high speed streams during the solar cycle. This leads to a distinct modulation of the average flow speed as already reported by Feldman et al. (1978). Our study also yields numerical estimates of quantities involving the particle densities, which have always been a problem in the past. We find that the modulations in the years from 1974 to 1982 (which include transitions through solar activity minimum as well as maximum) are also distinct though only minor. The proton flux, e.g., did not vary by more than ± 15 %. The increasing number of interplanetary shocks and other disturbances due to increasing solar activity since 1977 did not at all influence the solar rotation averages nor did they cause any enhanced scatter. This means that even huge deviations from the average often caused by interplanetary shock waves are compensated on a rather short term basis, i.e. within one solar rotation. Furthermore, we find it noteworthy that at times of maximum solar activity both the particle flux and the total energy deposited in the solar wind go through a minimum. There is also a definite modulation of the average α-particle content (confirming and extending the work by Feldman et al., 1978), which is most pronounced in the low speed wind. However, one should keep in mind that all these results may be valid only for a rather limited region of the heliosphere, since they were achieved from spacecraft moving only close to the ecliptic plane.

Finally I want to stress again the significance of certain deviations from the average. Of course there are the wellknown though not at all well understood interplanetary disturbances following solar transients such as flares and eruptive prominences. Apart from those even the "normal" acceleration mechanisms of the solar wind may eventually become dramatically changed as was demonstrated here. The existence of such strange though rare excursions from the average has certainly to be taken into account in any theory of solar wind expansion.

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Furthermore, I take the opportunity to thank the HELIOS mission operations teams both at GSOC (Oberpfaffenhofen) and at JPL (including the DSN of NASA) for their untiring efforts in getting down as many data as possible and keeping the spacecraft still alive.

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