

## The HELIOS 1 and 2 Solarwind Experiment Results

Summary Results after a 10 Year Observation Cycle



*Schwenn*



*Rosenbauer*

Rainer Schwenn's and Rosenbauer's subject is the solar wind. This is the continuous flow of charged particles leaving the sun and propagating outward. In average it consists of 95% Hydrogen ions (Protons), 4% Helium ions (Alpha Particles) and different ions of other elements, with an appropriate charge-equalizing number of free electrons. The velocity of this solar wind varies widely, in general between about 300 km/sec (slow solar wind streams) and about 900 km/sec (fast solar wind streams).

The solar wind originates in the very hot corona of the sun. We know that fast streams are released from the coronal hole regions characterized by low densities and open magnetic field structures, whereas slow streams are related to high density regions with closed magnetic field structures.

The solar wind experiment, denoted also as E-1 or plasma experiment, is a combination of several instruments for the measurement of low energy ions (three instruments) and electrons (one instrument). The measurement principle is simple: the charged particles run through an electrostatic or electrodynamic deflection system.

Only those particles arriving from specific directions and having a suitable ratio  $E / Q$  (kinetic energy to charge) can pass through in order to be counted by special detectors. The deflection voltage is varied step by step, thus shifting the transmission region. This results in a stepwise registration of energy spectra. The direction of particle arrival can also be determined.

Combining all these information results in velocity distribution functions for the different particle species. These functions are the basic data to deduce all important properties of the solar wind like velocity, density, temperature, composition, etc.

Up to the present all ion instruments have operated without any malfunction and without any fatigue. With some minor reservations this is also true for the electron instruments. The very thorough detector screening and handling has paid. Two instruments with overlapping measuring tasks but completely independent measuring methods do not show any relative sensitivity change. And this is the only possible

conclusion: none of the instruments has changed. Due to the long life of HELIOS-1 it has thus become possible to collect a set of solar plasma data of almost identical quality over the time span of a full activity cycle of the sun. Surely, this is one of the most complete and most comprehensive set of plasma data in the history of this field of research.

One of the earliest really new discoveries of HELIOS was that of the "strahl". Technically speaking, this is evidence for high anisotropy of the solar wind electrons. They exist together with isotropically distributed electrons which do not show distinct direction preferences. Fig. 2 is a plot of a typical electron distribution. It shows curves of equal particle velocity.

Also indicated by an arrow B is the direction of the magnetic field. Obviously the preferred direction is that of the field and we can distinguish between two classes of electrons, one class - they are somewhat faster than the others - following the magnetic field line and another class distributed nearly equally in all directions.

It is assumed that those particles which form the strahl by moving parallel to the magnetic field originate directly from the corona without having suffered any disturbance. It happens sometimes that the strahl disappears. In this case we must conclude that the magnetical connection into the corona is interrupted. It was another surprise during the mission to find singly-ionized Helium ( $\text{He}^+$ ) in the solar wind. Normally only double ionized Helium ( $\text{He}^{2+}$ ) is present. This is rather understandable, because the very hot corona - we have learned that its temperature is of the order of more than a million deg. C - does not allow  $\text{He}^+$  to exist. Fig. 3 clearly shows a third series of peaks besides those of protons (left) and  $\text{He}^{2+}$  (middle). The abundance of  $\text{He}^+$  compared to  $\text{He}^{2+}$  is 10% up to 30% in this case while the normal abundance is of the order of one millionth. How can these particles come from the corona of the sun where they cannot exist? We believe, the solution of this riddle is the magnetic field. In our example of January 29, 1977, a large shock had been observed a couple of hours earlier, following a great flare with a huge explosive mass ejection out of the corona. It could be that magnetically closed bubbles form during such an event. They could transport much cooler matter from chromospheric regions so fast through the hot corona that the material is not or not much heated, like a snow ball which is thrown through a flame. But many problems still exist there; e.g., why are such events so rare, twice in twenty years or so, while flares or protuberances combined with eruptions can be seen every few days?

Also "holes" could be found occasionally in the solar wind. During June 1980 suddenly the plasma density decreased dramatically. For nearly two days the instruments found almost no particles. The density went down to less than 1% of the normal. We do not yet have an explanation for this type of event.

There are also findings worth putting into a book of records: the slowest solar wind ever seen was measured by HELIOS 1 on November 17, 1979. For four hours its velocity dropped down to 170 km/sec (usually not under 300 km/sec).

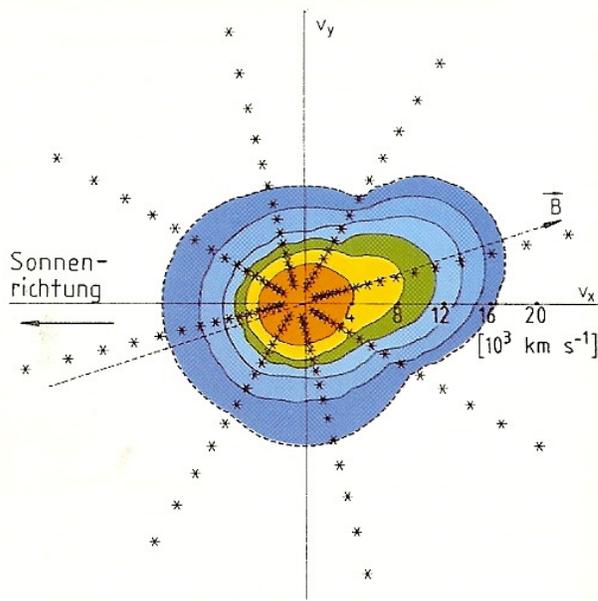


Fig. 2: Cut through a velocity distribution function of the electrons. The contour lines denote equal abundance (more precisely speaking: equal phase space density). Every line (from the center outward) relates to a decay of one tenth of the prior value. The asterisks mark the position of the measuring channels. The dashed line indicates the momentary direction of the interplanetary magnetic field. Regard the "bump" at the right and opposite side of the sun. Into this direction, i.e., into the direction of the magnetic field, many more electrons are running than in any other direction. This is the "strahl" of the electron distribution.

The highest ever measured plasma density was found close to the perihelion on May 29, 1980 shortly after a shock wave, with more than 1000 particles per cm<sup>2</sup>. This is about 10 times higher than the normal speed.

Fig. 4 gives nine examples of velocity distribution functions of protons, as they have been measured directly related to the magnetic field direction. Quite symmetrical distributions can be found as well as strongly irregular distributed directions. Of course, those velocity components are meant to be superimposed on the bulk velocity of the solar wind. Quite often two different kinds of protons occur, one of them up to 60 km/sec faster than the other.

This tendency increases closer to the sun: sometimes one kind of protons is about 300 km /sec faster than the other. Helium ions can also be found to be faster. Several questions arise from these findings. Most of them cannot be answered yet: Why, for example, is one portion of the particles accelerated, the other not? How get the particles decelerated on their way out?

The overall structure of the heliosphere, especially its central region, can now be far better described than a few years ago, although even now the image is still incomplete Fig. 5 shows the 7.3 deg inclined sun together with the orbiting earth. The polar regions of the sun are covered with large coronal holes. They stretch far down to the equatorial zones. The two polar caps show inverse magnetic polarity. The "active" regions of the sun (e.g., the sun spots etc.) lie along the equatorial belt. Here the magnetic field lines are predominantly closed. Field lines originating in the coronal holes are almost completely "open". They are pulled far out by the solar wind, possibly to the outermost boundaries of the solar system. Thus a sheet-like, warped boundary layer is generated separating the regions of influence of the northern and southern solar hemisphere.

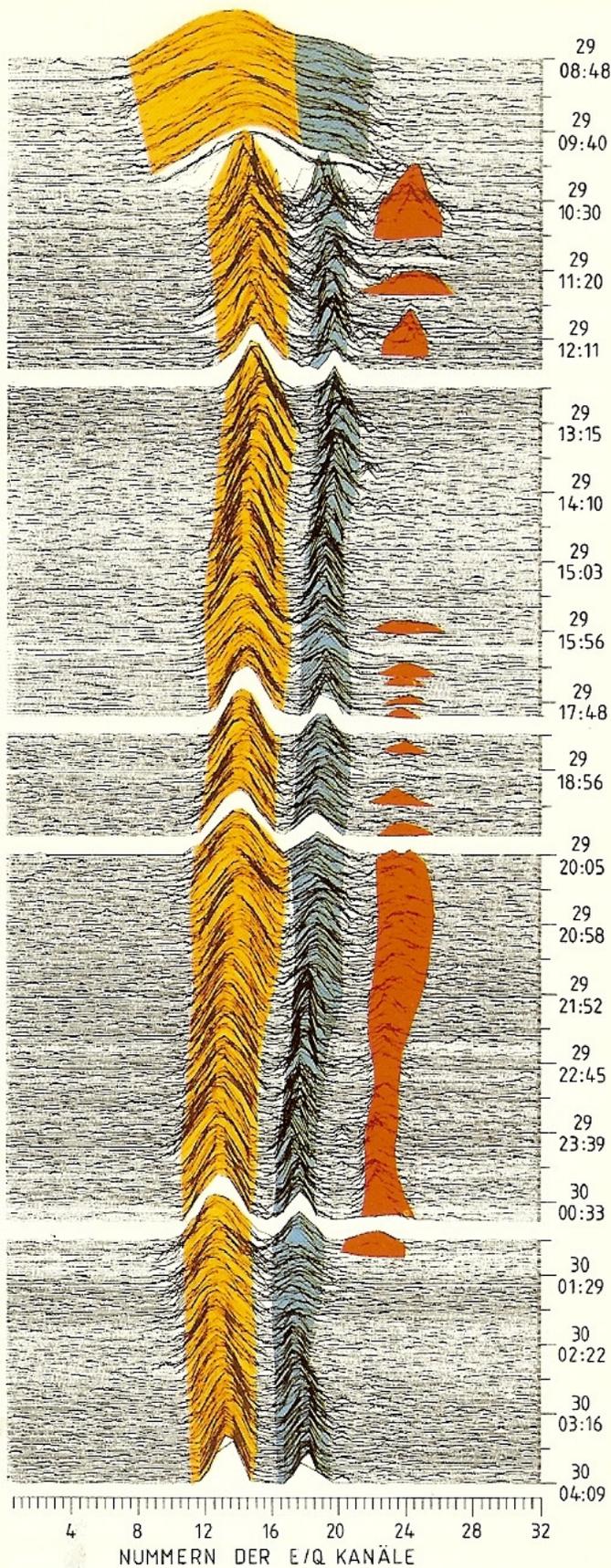


Fig. 3: This is a consecutive series of ion spectra. Regard the unusual appearance of a third component (right) besides the protons (left) and doubly charged Helium ions (alpha particles; middle)- Only these two species are typical for particle distributions in the solar wind. The particles of the unusual component are singly charged Helium (He+) ions. This gas is suspected to originate from the "cold" chromosphere. The measurement was made by HELIOS 1 on Jan. 29 and 30, 1977.

During the last solar minimum, 1975/76, the north was magnetically positive the south negative.

The field lines directed nearly radially outward from the sun are deformed to archimedean spirals due to the rotation of the sun. The Swedish Nobel laureat Hannes Alfvén has compared this model, the "Ballerina-model" of the heliosphere with a dancing ballerina. Her swinging skirt relates to the warped boundary layer, rotating with the sun and stretching out far into space. The intersecting lines between the magnetic boundary layer are called sector boundaries. It was very surprising for the scientists analyzing the data, when they found that the transfer regions between low and fast solar wind streams get narrower close to the sun than at earth distance.

Most theoretical considerations had expected a widening of those regions.

Fig. 6 explains the ballerina model under another aspect. The lower box shows a coronal map of the sun. The north and south coronal holes are well established. In between regions of closed magnetic fields occur. Included are also the orbit projections of the earth and of HELIOS 1. The tickmarks indicate the passage time of the respective body. Both orbits cross over regions with open and closed magnetic structures.

The upper box shows the velocities of the solar wind as measured by HELIOS and close to the earth by IMP 7/8. There is a close correlation visible between high velocity streams and coronal holes. The curves of HELIOS and IMP 7 (Erde) do also not differ too much, except in the region which is indicated by the arrow. Here the earth observes continuously high velocities while the velocity measured on HELIOS drops down to very low speeds.

Apparently the earth had continued staying in the regime of the southern coronal hole, whereas HELIOS has changed over into a region of closed field lines. During the summer of 1976 the very minimum of the solar activity had been reached. The equatorial extensions of the polar coronal holes had retired back to the poles. The skirt of the ballerina sun must have hung almost without folds in the equatorial plane of the sun. Along the orbits of the HELIOS probes the fast streams had disappeared. This structure changed when the solar activity began to increase in 1977. The ballerina's skirt must soon have looked very crumpled. As expected, the solar magnetic field's polarity reversed in 1980, at the peak of the sun's activity.

The period of this magnetic solar cycle is double that of the well-known cycle, i.e., 22 years. Often when HELIOS passed through a magnetic sector boundary the already mentioned strahl disappeared for some time. Here, apparently, the magnetic field lines normally tracing back to the sun are interrupted. Most probably field line reconnection occurs, the merging of magnetic field lines, as to say a magnetic short circuit.

The solar maximum of 1980 turned out to be higher than expected. The relative sun spot number - this is the common measure for the solar activity - went up to its highest value for 23 years. It was due to the special orbit of HELIOS 1 that it was positioned above the west or east limb of the sun most of the time (the perihelion passage-time, which occurred before or behind the sun in that period is short compared to the rest of the orbit - see also Fig. 7. This offered the chance to compare events registered on board directly with coronagraph observations.

We found that eruptions releasing particles into the direction toward the spacecraft is mostly followed by a strong shock at HELIOS 1. However, the correlation is not always unambiguous because there were often many shock waves one after the other.

From the arrival time at HELIOS the average velocity of the shock can be calculated. In almost every case it was higher than the momentary shock velocity at the position of HELIOS. Mostly the velocity measured by the coronagraph is still higher.

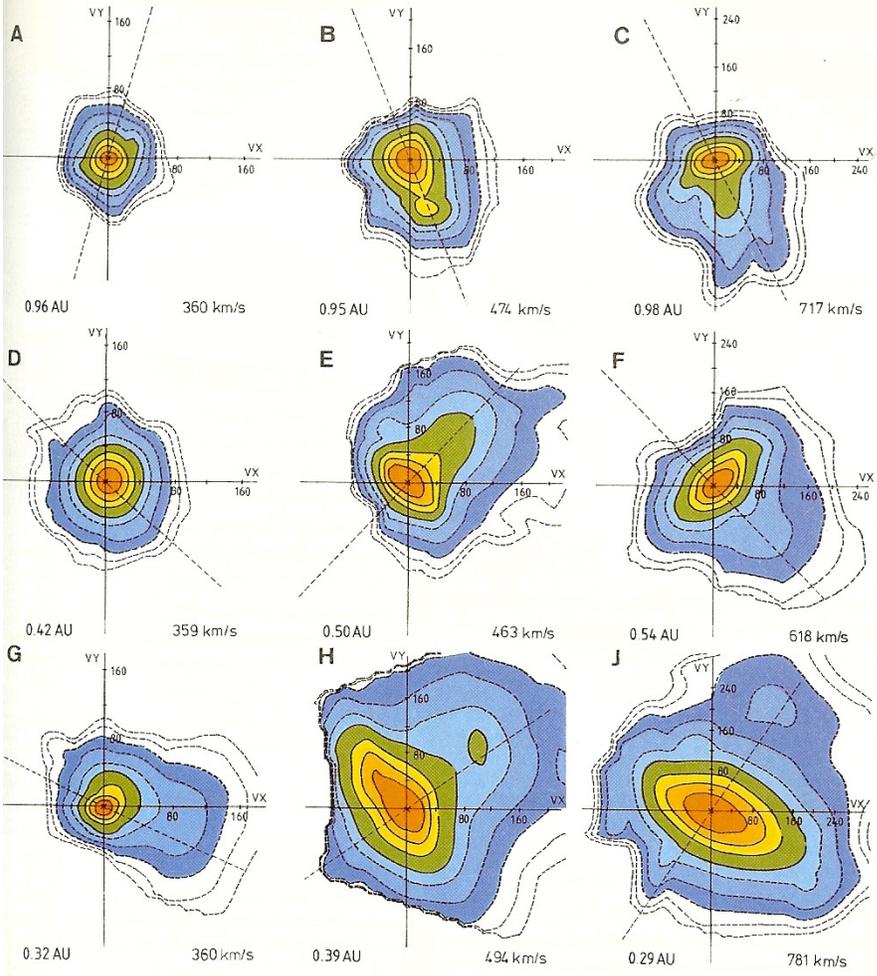


Fig. 4: Some typical examples of velocity distributions of protons. The plots are similar to those of Fig.2, although they relate to another particle species. The sun's position is on the left. For these two dimensional plots the distributions which are really three dimensional, are cut in such a way that every sectional plane contains the momentary interplanetary magnetic field (dashed line). From the top down the examples are arranged for the solar distance (1 AU =average distance sun -earth) resp. from left to right for the solar wind velocity. A and D are isotropic distributions, B, H, J are distributions with a double peak, i.e., with a fast second component, E, F, H, J show strong anisotropies in the center of the distribution.

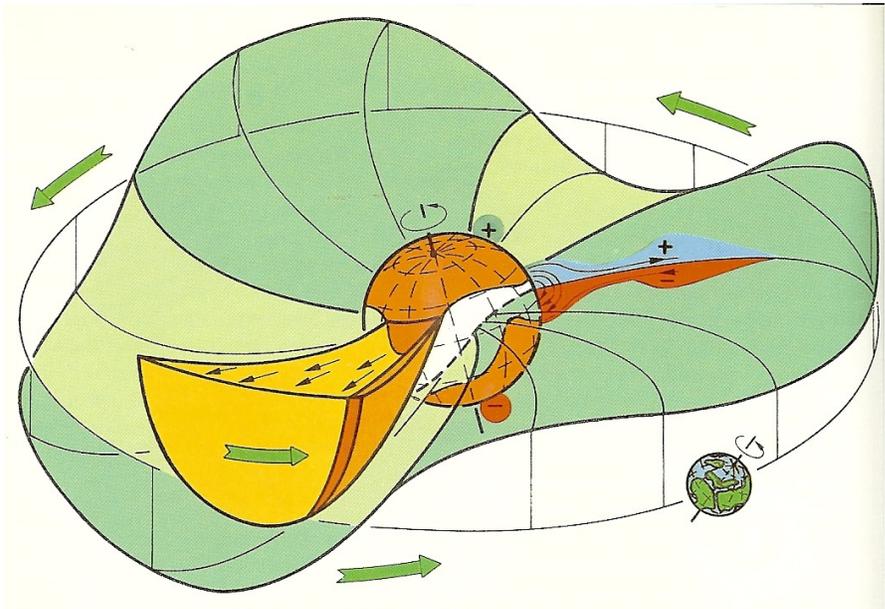


Fig. 5: The sun as a ballerina. This sketch - not in scale - is a model of the solar system close to the minimum of sun's activity. Above the sun's poles one can see coronal holes with opposite magnetic polarity. Same excursions reach down to the equator. The "ballerina's

That means, the shock wave decelerates when propagating outward; how much depends on the conditions of the medium the shock has to pass through.

Especially after giant flares the velocities can be very high: on Nov. 26, 1982, we measured more than 2000 km/sec. (the record is still with the shock of Aug. 4, 1972, when more than 2500 km/sec was determined). In such cases the ejected matter races almost unbraked like the bullet of a gun outward, driving the shock wave in front of it. Strong shocks can stretch out longitudinally far around the sun, as was observable thanks to the double mission of HELIOS 1 and 2. An extension of more than 90° from the flare location was not infrequent. Following the huge flare of April 4, 1981 even at an angular distance of 140° a shock could be registered. The whole heliosphere had been thoroughly shocked by the shock wave of one single flare!

But the contrary happened also: HELIOS 1 sometimes found a shock, but not so HELIOS 2 although their distance was only about 30° apart. Very slow eruptions occur also. They are released not so much by flares but by suddenly bursting protuberances. Often their speed rises considerably in the viewing field of the coronagraph.

The ejected matter is pushed forward over a long time. It is not a shot out of an explosion as in the case of a flare. However, when arriving at HELIOS the gas has been decelerated again (Fig. 8). We do not yet know very much about flare releasing or protuberance bursting processes.

Obviously, the magnetic field plays a key role with its huge abundance of energy. As another consequence of shock waves magnetic clouds have been found in the interplanetary plasma. These are bubbles of closed magnetic field line rings travelling out into space, also discussed in the article by Mariani et al. (Helios Experiment 3).

Since the early days of space research the problem is open as to how the sun can trigger the intensity of the cosmic radiation arriving in the solar system from far out in the galaxy: the intensity of the cosmic radiation is high when the solar activity is low and vice versa.

We know that the solar wind is the connecting link; but how does it act? Fig. 9 gives the variances of averages of four characteristic parameters of the solar wind from 1974 until 1982:

The proton velocity  $v_p$  the proton density  $n_p$ , the proton flow density  $n_p \times v_p$  and the total energy  $E_{total}$ . None of these parameters shows drastic variations, especially compared to the high degree of modulation of the cosmic radiation.

The variation of all four parameters is not larger than about 15%. This cannot be significant enough for this triggering. However, there is another explanation. As we have seen already, shock waves can stretch out over nearly the full sphere. They travel outward and by merging together they might form a shell around the whole heliosphere.

During solar maximum they are very numerous always soon replacing a decaying shock wave by one which is following. This shell might act like a shield hindering the particles of the cosmic radiation to penetrate into the inner solar system. During solar minimum shock waves are rare events. The shell of shock waves can no longer

skirt" is the separation layer between positive and negative magnetic field lines connected outward by the solar wind. Number and size of the folds relate to the shape of the coronal holes in relation to the active belt in between. The whole structure rotates with the sun about its somewhat inclined axis. The coronal holes are the sources of particularly fast streamers in the solar wind. A sector of such a structure is indicated in the left half of the figure. At the front side of the stream a billow of condensed plasma collects.

form, allowing the particles to move inwards. The high quality of the detectors of the plasma experiment made it possible to determine a very important cosmological number. They succeeded in delivering the fundamental data necessary to calculate the loss of sun's angular momentum caused by the offstreaming solar wind. .

Each wind particle moves out only almost radially. The small azimuth component has to be delivered by the angular momentum of the sun.

By thorough averaging over many years of data this value has been found to be  $2 \times 10^{22} \text{ N m/sterad}$ . This is the continuous average loss of angular momentum of the sun.

From this result we know now that the sun is able to stay rotating about its axis for another couple of billion years. The value of the angular momentum defines the critical point, i.e., the distance from the sun, where the solar wind particles are leaving the co-rotating corona to start travelling outward as the solar wind. This should be at about 12 solar radii. However, if one tries to figure out this distance separately for fast and slow solar wind, one gets the surprising result that close to the sun almost the whole angular momentum loss is given to the slow wind. Its critical point should be as far out as 30-40 solar radii, while the critical point of the fast wind is supposed to lie much closer inwards. Thus the different kinds of the solar wind originate from different altitude regions of the corona. We come to this conclusion also by a completely different observation:

Fast solar wind contains on average 3.6% Helium, slow solar wind only 2.5%. Many of the results, especially of the surprises we have presented here, have been gained during mission phases, for which nobody had planned, and when the eighteen months of the planned "extended" mission had long passed.

Many questions that might have been answered by HELIOS are still open. We therefore hope that HELIOS 1 remains alive at least until the mission ULYSSES, a space probe destined to travel out of the ecliptic plane and over sun's poles, has been launched. This would give us the chance to intercalibrate the plasma-experiments of both missions in order to continue and extend the observations obtained by HELIOS.

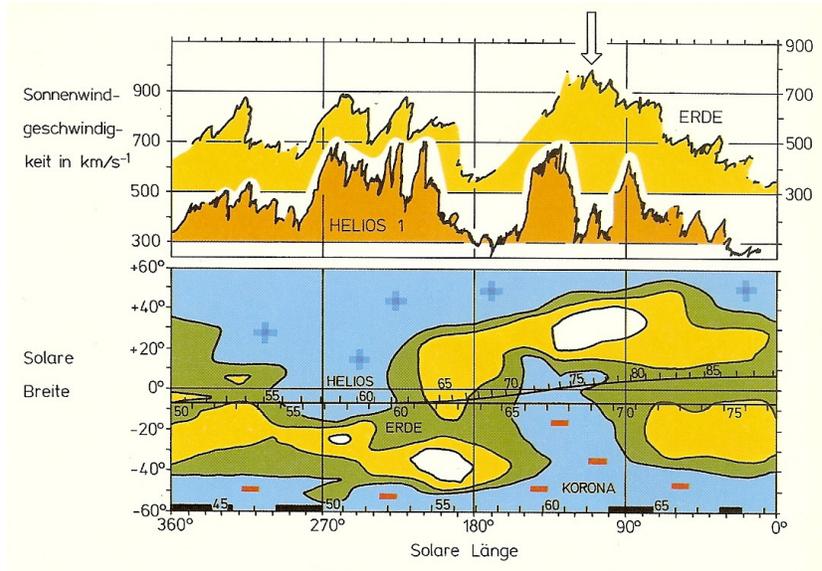


Fig. 6: Structures in the solar wind end their sources in the corona. The lower part of the figure is a "solar map" showing the extension of the coronal holes (blue) in March 1975 together with the orbit projections of the earth and HELIOS 1. The tickmarks signify the day of year. In the upper part the velocities of the solar wind are plotted as measured by HELIOS 1 and by the earth satellites IMP 7 and 8, corrected for the plasma time-of-flight between the sun and the measuring position. Easily detectable is the correlation between regions of "fast" solar wind and the coronal holes. The arrow in the right part of the figure is pointing to the time of closest solar approach of HELIOS 1, when the spacecraft apparently had arrived in the northern outer periphery of the fast stream. This stream still hits the earth intensively 10 degrees more to the south. Measurements of this kind have shown that the boundary layers between fast and slow streams are scarcely thicker than 3 degrees.

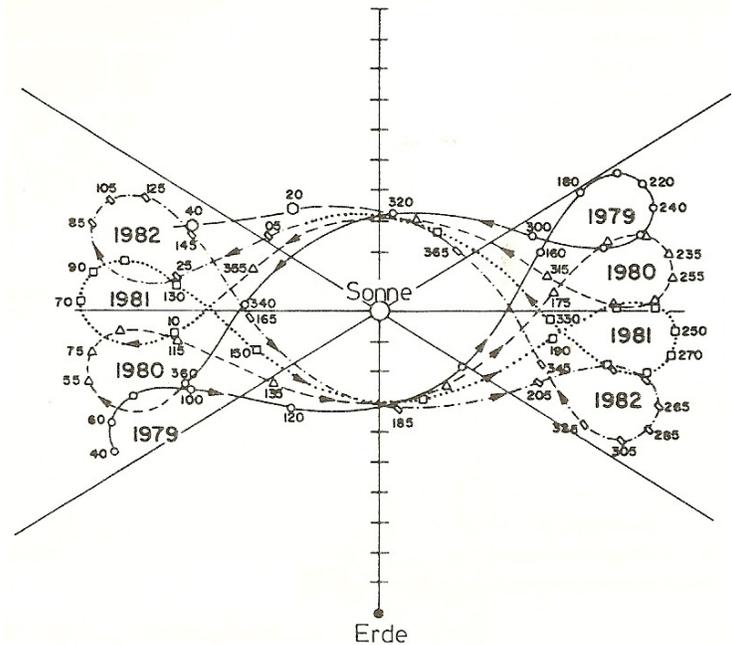


Fig. 7: This was the orbit of HELIOS 1 as seen from the earth (at bottom) in 1979 to 1982. With interruptions only about 30 days around the perihelia the spacecraft position was almost constantly in a narrow region over the left (east) or right (west) limb of the sun.

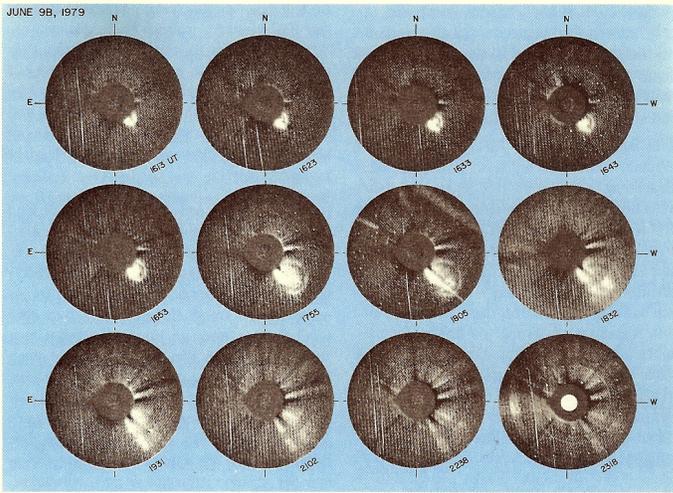


Fig. 8: The coronal event of June 6, 1979 as an example of a "slow" mass ejection. For several hours the coronagraph of the NRL (Naval Research Laboratory, Washington D.C.) saw a big bubble-like feature growing. The forefront of this feature arrived at the rim of the viewing field after 18.32 h, but was further growing strongly. In the Fig. 5 in the lower right the size of the sun is shown for comparison. It is easily seen that at first the velocity of the forefront was low (about 310 km/sec). Between 16.53 h and 17.55 h it grew considerably higher (590 km/sec). The correlating shock arrived at HELIOS 1, 130 solarradii apart, 52 hours later. It had meanwhile clearly again decelerated.

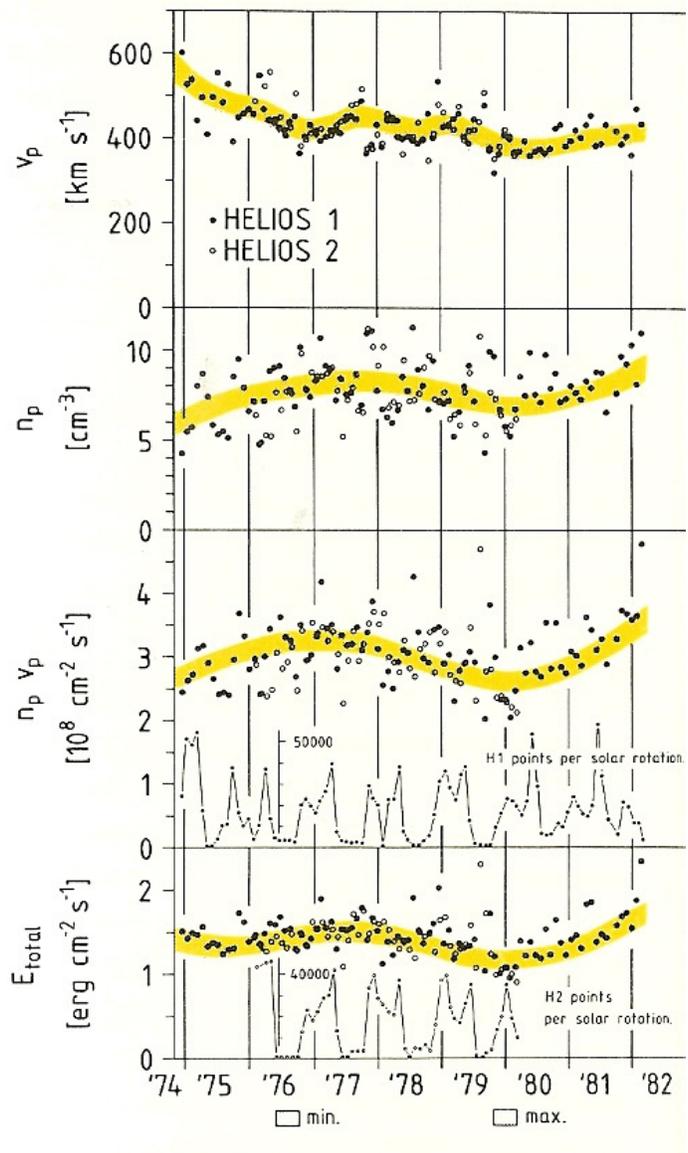


Fig. 9: Here all 2,515,463 spectra are put together from the end of 1974 until Feb. 2, 1980 (since then we have quite a few more). Each point represents an average over a full solar rotation. The value changing most clearly in the whole time span is the average velocity of the solar wind (top). The particle density (second plot) and the particle flow density (third plot) show much higher scatter. But their averages fluctuate only by about 15%. With the plot at the bottom it is shown that the solar energy provided to release the solar wind was lowest in 1979/80. This was the period of maximum activity, when the number of energy-rich flares was highest.

The above article is a reprint of the HELIOS publication celebrating the 10th Anniversary of the launch of Helios-1 on December 10, 1974 honouring the 40th anniversary of the launch in December 2014. The original article and all the other Helios-1/2 results have been published in the book "10 Years HELIOS" (ISBN 3-88135-156-6) was edited by J. Kehr for publication in the "Journal of Space Operations & Communicator". In case of discrepancies to the original article the original (German-) text should take precedence.