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HELIOS SOLAR PROBES SCIENCE SUMMARIES

A brief description of the principal results
of the HELIOS INVESTIGATIONS
through the first five years of the missions
and a bibliography of the principal publications
for each of the experiments

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National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

PREFACE

This book presents a brief description of the Helios mission, its experiments, and a summary of the results of each investigation up through the summer of 1979. A bibliography of the major papers published by each investigation team is included. This bibliography is most important, since the investigator results have been published in a diverse collection of journals and books.

At this point, the Helios solar probe missions are clearly a large success. The spacecraft and all the experiments have performed well for years beyond their design lifetimes. Both spacecraft were launched during a very quiet solar minimum. For the first 18 months, the investigators received data which allowed an excellent characterization of space in the inner solar system during quiet times. We are now well into the solar maximum phase, and the conditions in our inner solar system have markedly changed. Active phemonena are often observed at the rate of several per day, versus one a month in 1974.

One cannot stress enough the importance of the fact that these missions allowed the observation of solar and galactic phenomena with the same experiments from solar minimum through solar maximum at a large variety of solar azimuths and elevations with respect to the Earth. Of particular interest are the data at and behind the west limb of the Sun.

It's obvious that the managers, engineers, scientists and contractors did an excellent job on the spacecraft and experiments. It is also very obvious to the experimenters that the mission controllers and data processing personnel at the German Space Operation Center, the Jet Propulsion Laboratory and the Goddard Space Flight Center have performed in an outstanding fashion for more than 5 years. We gratefully acknowledge their contributions and share in their success.

James H. Trainor
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A Short Review of the Overall Scientific Tasks and of Some General Principles of HELIOS

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The two Helios probes (Fig. 1), launched December 10, 1974, and January 15, 1976, by Titan IIIE/Centaur D1T/Te-364/4 rockets, were built as a joint venture of the United States of America and the Federal Republic of Germany. The overall scientific task was the investigation of the innermost regions of interplanetary space. Thus, the two probes were the first, and hitherto only, space vehicles approaching the Sun as close as 0.31 AU and 0.29 AU, respectively.

The payload of each of the two probes consists of the experiments decribed in the following chapters by the investigators themselves.

The payload can be divided into three groups of experiments representing three main research fields:

(1) plasma experiments (Experiments 1 through 5) for the observation and investigation of the particles and fields of the solar-interplanetary plasma (protons, alpha particles, electrons, magnetic and electric fields and their fluctuations;

(2) cosmic ray experiments (Experiments 6 through 8) for the study of characteristics of solar and galactic cosmic rays, including an X-ray monitor and (on Helios-2 only) a gamma-ray burst experiment; and

(3) micrometeorite experiments (Experiments 9 and 10), to remotely investigate the interplanetary dust by an optical system, as well as in situ by a particle detector and analyzer.

To supplement the on-board experiments, Helios is involved in some passive investigations, as well:

(1) a celestial mechanics experiment for the study of relativistic effects (Experiment 11), and

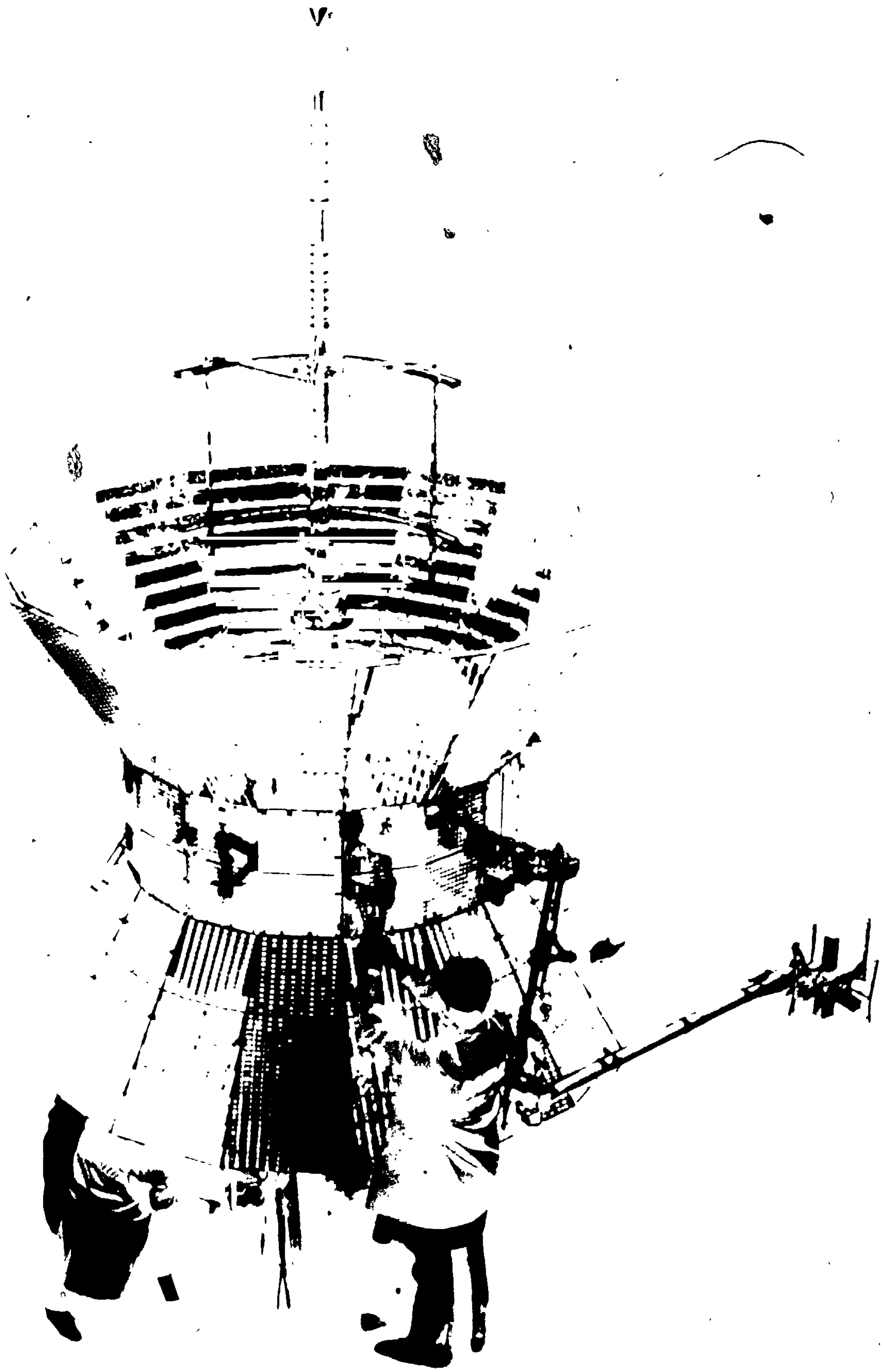

Fig. 1

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(2) coronal sounding (Experiment 12) by investigating the Faraday rotation of the S-band signals of the two probes wherever one of them is in an orbital constellation near superior conjunction, and by analyzing time delay effects, including Doppler and DRVID.

The two probes have highly eccentric heliocentric orbits (Fig. 2). The orbital period is 190d for HE-1 and 186d for HE-2. Due to the distance variation of a factor of 3, the orbital velocity varies also by a factor of 3. This results in a very high angular velocity of the probes in the perihelion regions. However, whereas the relative angular velocity between the Sun's rotation and the Earth's revolution is about 2.4×10^{-6} sec^{-1}, it is only half as large between the Sun and Helios in its perihelion regions. In other words, in the perihelion regions Helios is not only closer to the Sun by a factor of 3 compared to the Earth, but is also relatively slower, as seen from the Sun by a factor of 2. This improves the ability to discriminate between temporal and spatial solar structures. However, this is only valid for the azimuthal motion of the two spacecraft; the axis of the Sun is inclined by about 7.5 degrees to the normal of the ecliptic. This causes a latitudinal motion of the spacecraft with respect to the Sun. The respective velocity of the Earth is nearly constant. By chance, the angle between solar-ecliptical mode and the line of apsides of HE-1 is only about 4^{o}; therefore, the latitudinal velocity of HE-1 is very high in the perihelion phase (Fig. 2). The maximum value is 0.9^{o} per day. Within 17 days during the perihelion phase, the latitudinal change is 12^{o}; therefore, Helios is a sensitive tool for latitude-dependent solar phenomena, in spite of its ecliptic orbit.

Both Helios spacecraft were launched in the outgoing phases of Solar Cycle 20. The ruling state during the primary mission was that of sunspot minimum condition. From the end of 1976 on, the sunspot number has continuously increased. This increase is considerably steeper than the preceding Cycle 20; therefore, an extremely high solar maximum has been predicted for late 1979 through early 1981.

Since both Helios spaecraft are alive and in good condition, they offer the unique opportunity of investigating the state and the dynamics of solar interplanetary space over almost one full solar cycle. The cycle has turned out to be one of the most interesting observed since the end of the 18^{th} century.

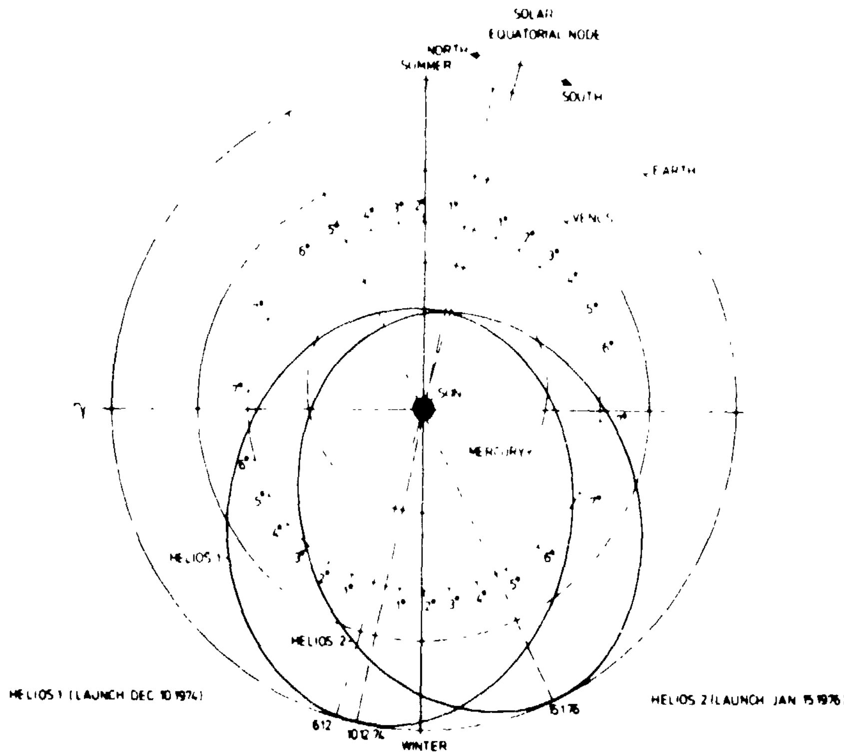

Fig. 2. Projections on the ecliptic plane for the first orbits of Helios-1 and -2. The orbits of Earth, Venus and Mercury are shown, as well as the solar latitude of the Spacecraft as a function of subsolar azimuth.

Because of the very good ground station coverage, combined with the use of on-board memory (at very low bit rates), an almost continuous data stream can be achieved. This data set should be completed with similar comprehensive data of interplanetary phenomena during solar maximum in order to contribute to a better understanding of solar-terrestrial relationships.

Many cooperative programs are planned involving Helios for as long as at least one spacecraft performs. The Helios experimenters are cooperating with the SCOSTEP (Scientific Committee on Solar Terrestrial Physics), especially during the so-called STIP intervals (Study of Traveling Interplanetary Phenomena). For the Solar Maximum Year, cooperative programs have already been negotiated with SMM (Solar Maximum Mission) providing the spacecraft remain in good shape and data recovery continues.

In addition to the research work done by the Helios investigators themselves, the data obtained by Helios are used world-wide as reference data in interplanetary research of missions such as ISEE and SMM.

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THE PLASMA EXPERIMENT ON HELIOS (E 1)

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A. Short Description of the Instruments and their Primary Purpose

The Plasma Experiment aboard the Helios solar probes consists of four independent instruments designed to investigate the interplanetary plasma, the so-called solar wind; primarily, the velocity distribution functions of the different kinds of particles are measured. All important hydrodynamic parameters of the solar wind plasma can then be derived. These measurements at varying distances from the Sun are suppying new data which will support and improve our understanding of solar wind expansion.

Three instruments analyze the positive components of the solar wind (protons and heavier ions with energy-per-charge values from 0.155 to 15.32 kV). Two of them allow for an angular resolution in both directions of incidence. One instrument measures electrons in the energy range from 0.5 to 1660 eV with a one-dimensional angular resolution.

Since the launches in December 1974 and January 1976, respectively, all the instruments, which are partially novel developments, perform very well on both probes. There is no degradation of any detector yet; a partial malfunction in the electron instrument on Helios-2, starting after 18 months of operation, is of minor importance. We see an excellent chance for the instruments to work well through the upcoming solar activity maximum.

B. Highlights of the Results

(1) Structures in the Solar Wind

During the declining part of the past solar cycle, the solar wind stream structure was governed by two big high-speed stream systems which remained remarkably stable for many solar rotations in 1974 and 1975. They emerged from equatorial extensions of both polar coronal holes which were detected during the Skylab mission in 1973/74. During the first approach of Helios-1 to 0.3 AU in early 1975, we found from direct comparison with data simultaneously measured from the IMP-7 and -8 Earth satellites that the leading edges of fast streams appear much steeper at 0.3 AU than at 1 AU. This is in contrast to current theoretical models. In addition, we could prove that there are also very sharp latitudinal stream boundaries. Obviously, fast streams are separated from slow plasma on all sides by thin boundary layers at 0.3 AU. This suggests that there exist different acceleration processes for slow and fast stream plasma with no intermediate stages close to the Sun.

Nearly continuous data from the Helios-1 and -2 double mission, combined with similar data from Earth satellites and other space probes (Pioneers, Voyager 1 and 2), give us a unique opportunity for studying stream evolutions in interplanetary space. Thus, we could quantitatively show how stream fronts are deformed and deflected. We found significant deviations from purely radial flow. Based on a quantitative analysis, we could even predict in a few cases the arrival of stream fronts at the Earth and their associated geomagnetic disturbances with an accuracy of a few hours.

A special collaboration between Helios and Voyager experimenters on some events in November 1977 revealed some new aspects which otherwise might have been overlooked. A small corotating fast stream originating in a coronal hole was observed as it moved from 0.7 to 1.6 AU. The stream interface and the extraordinary shockwave in front of it corotated from 0.7 to 1.6 AU, persisting even though the stream itself had dissipated at 1.6 AU.

(2) Radial Gradients of the Plasma Parameters

Eight radial line-up constellations between Helios-1 and -2 occurred in the years 1976 and 1977. From the short periods of "plasma line-ups," when the plasma seen from the inner probe also encounters the outer probe, radial gradients of the plasma parameters could be obtained directly. We found significant differences in the average gradients between the slow and the fast solar wind: In the slow plasma (up to 400 kms^{-1}), the flow speed v_p increases by (52±11) kms^{-1} per AU and the proton temperature T_p decreases as $r^{-1.2}$[illegible], i.e. nearly adiabatically. In the fast plasma v_p remains nearly constant, and T_p decreases as $r^{-0.69\pm0.08}$. Further differences are found in the general shape of the distribution functions and their changes with radial distances, as well as in the properties of the α-particle component.

This analysis is now generally being confirmed by statistical methods using all the available data. The whole set of observations supports the hypothesis mentioned above that the solar wind might be a two-state phenomenon, with possibly two different acceleration mechanisms.

(3) Three-dimensional Velocity Distribution Measurements of Solar Wind Protons

The main instrument for positive ions, with its resolution of energy and both angles of incidence, allows the analysis of the full proton distribution function in an unprecedented way. We found that in high-speed streams there is a pronounced temperature anisotropy characterized by a higher temperature perpendicular to the local magnetic field rather than parallel to it. This effect, which has been interpreted as a signature of waves affecting the protons, is even more distinct close to the Sun.

Often a bulge, or even a second hump, in the distribution can be detected. Its velocity relative to the main peak is always directed along the magnetic field and seems to be closely related to the local Alfvén speed. The occurrence of this bulge seems to be well-correlated with the excitation of ion-acoustic noise which is detected by the Helios wave experiments. A plasma physical stability analysis was carried out showing that the observed type of distribution functions is, indeed, marginally unstable versus the ion acoustic wave mode.

(4) Solar Wind α-particles

The Helios instruments combine high resolution and sensitivity with low background noise. This makes it possible for the first time to measure the velocity distributions in three dimensions even for α-particles, although their content in the solar wind is only 4%. There was a tendency found for the α-particles to be faster than the protons in high-speed plasma. The speed difference is always aligned with the magnetic field and has the value of the local Alfven speed which can reach values up to 300 km/s close to the Sun. It seems that the α-particles move through the proton "fluid" with the phase speed of the Alfven waves, similar to a surfer in front of ocean waves.

(5) Interplanetary Shock Waves and Discontinuities

Along with solar activity, the number of solar flares producing interplanetary shocks increased significantly after the broad activity minimum in the summer of 1976. Some of them are of particular interest for the study of shock propagations and interactions, as well as the acceleration of particles along shocks, since they were observed from several spacecraft spread between 0.3 and 3 AU. We are participating in several international study groups concentrating on some spectacular events in late 1977 and early 1978.

The new solar cycle is apparently starting off quite lively, providing us a series of flare and shock events for which a unique data coverage from several spacecraft is available. This might bring us towards a better understanding of flare phenomena and their interactions with the interplanetary medium.

C. Outlook on Possible Results during Solar Maximum

Since the delayed end of the old solar cycle in late 1976, the solar wind stream structure did change significantly. No longer are stable, broad, high-speed streams observed corotating in a stationary manner for more than one or two solar rotations, as they were in 1975/76. Now the structure is apparently broken up and scattered in many minor irregular streams. It has always been an unsolved problem what the influence of solar activity on solar wind expansion might be. Up to now no correlation of average solar wind parameters with solar activity could be proven, although there is the well-known modulation of cosmic ray intensities during the solar cycle which somehow have to be coupled to the solar wind. It may well be that it is not the average solar wind, but the difference in stream structure and interplanetary interaction processes that connects solar activity with cosmic ray modulation. The Helios mission could provide us a set of data covering the declining part of a solar cycle, the minimum, the onset of the new solar cycle, and possibly even its maximum. This data set is unique not only because of the Helios orbits: One should note there are nearly no gaps in the data (in terms of one-hour averages) because of excellent ground station support which can be maintained mainly through the DSN 26 m stations and the Weilheim 30 m station. In addition, due to the thorough use of the on-board memories, any station gap can be covered at lower bit rates. For the first time, continuous data during solar minimum and maximum can be obtained using identical instruments. Thus, the persistent problem of intercalibrating different instruments of different experimenters can be avoided in this case.

The upcoming solar maximum will be t topic of a big international cooperative effort which unites scientists of a broad variety of disciplines during the "Solar Maximum Year" (SMY) from August 1979 to February 1981. One out of three subprograms of SMY is the Study of Traveling Interplanetary Phenomena (STIP), which was established in 1973. Several special periods for STIP were selected based upon unique opportunities generated by fortunate interplanetary constellations of the Helios probes and other spacecraft. The results look promising. This will intensify the activities of STIP during SMY, and the scientific community is looking forward to both Helios probes participating as long as possible.

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CALCULATION OF THE DISTURBANCES OF THE LOW ENERGY ELECTRON MEASUREMENTS (E1-Z)

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Introduction

The measured spectra (E1) of the low-energy solar wind electrons are disturbed by potentials in the vicinity of the Helios spacecraft and partially superposed by photoelectrons. The measured energies of the solar wind electrons are shifted by the spacecraft potential which can be estimated from the spectra only in some special cases; therefore, theoretical models have been developed to describe the interaction between the plasma and the Helios spacecraft.

The measurements of the solar wind electrons with low energies are disturbed by the spacecraft. There are electric fields in the vicinity of the spacecraft and a potential difference between the instrument (U_s) and the distant undisturbed solar wind plasma ($U_p = 0$). Consequently, all solar wind electrons counted by the electron instrument have been accelerated by these fields and are observed with a shifted energy $E_s = E_p + e(U_s)$.

Figure 1 gives an example of these observed spectra. In this case, the spacecraft potential U_s is positive, so that no solar wind electrons have been counted with energies below $e(U_s)$.

Another problem arises from the emission of photoelectrons from the surface of the spacecraft. Some of these photoelecrons are directed into the instrument and result in great count rates in the corresponding low-energy channels. In Figure 1, photoelectrons are observed when the instrument is on the illuminated part of the Helios probe.

The most important conditions for the interpretation of the measured spectra are:

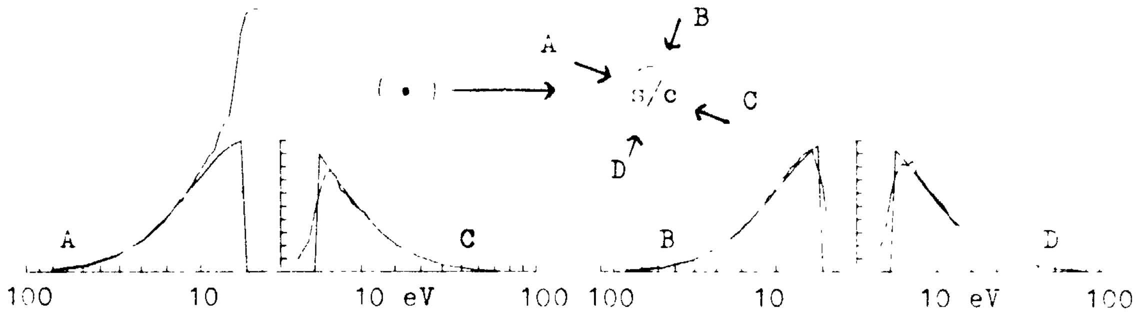

Fig. 1. Orthogonal profiles of the electron distribution F(v). The measured values of F(v) are plotted together with a fitted Maxwellian, which is zero for energies below the spacecraft potential.

(1) the knowledge of the spacecraft potential, U_s, and

(2) the capability to separate the energy region where photoelectrons are measured from the domain of the solar wind electrons.

In some special cases, these items may be deduced from the data. In general, however, they are not known. Therefore, theoret al models had to be developed to describe the interactions between the plasma and the Helios spacecraft.

Calculations of these effects must be based on the nonlinear Vlasov-Poisson-system of partial differential equations for collisionless plasmas. Steady-state solutions require the condition that the electric currents on the surface elements produced by the various plasma components are compensated. This compensation results in the floating potential for each surface element.

Although it is not possible to obtain a self-consistent solution for the complex geometry and surface properties of the Helios spacecraft, the dominant features can be estimated by means of simplified models.

Such a model can be treated with the numerical plasma simulation (Fig. 2) in order to obtain the potential in the vicinity of the probe (Fig. 3).

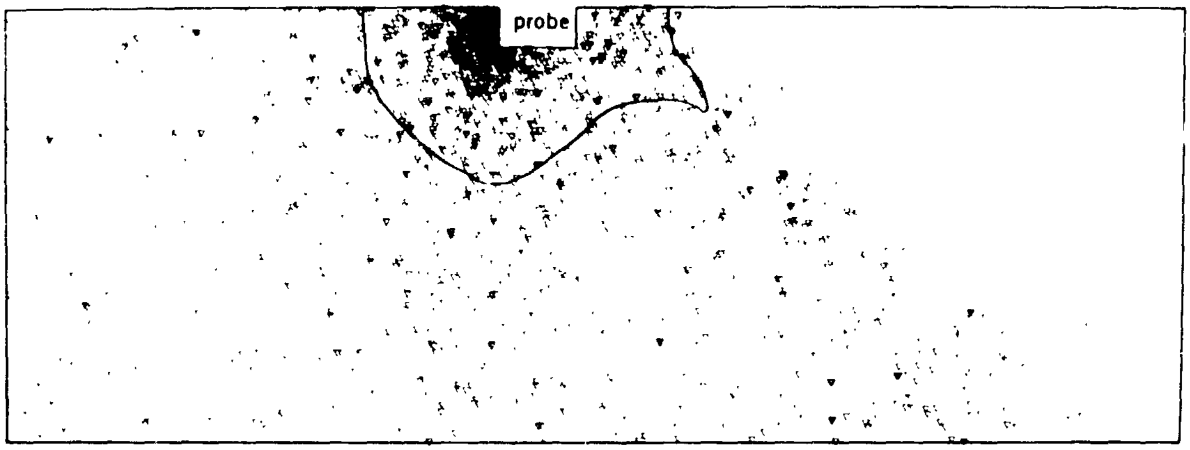

Fig. 2. A "snapshot" from a computer simulation run. Each dot gives the position of a simulation particle representing approximately one million photoelectrons emitted from the front (left side) of the probe. The photoelectron density exceeds the solar wind density in the near surroundings of the spacecraft.

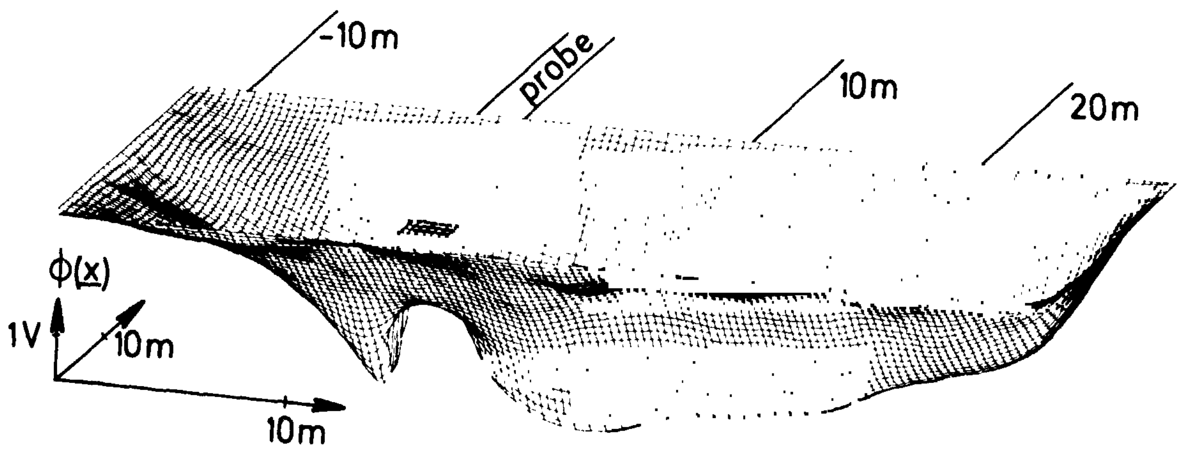

Fig. 3. Potential in the vicinity of the probe (perspectivic representation). The dense photoelectron cloud (c.f. Fig. 2) and the wake behind the spacecraft produce potential barriers around the probe, where the potential is lower than the spacecraft potential. This effect is important for the disturbance of the measurements.

This illustration demonstrates potential barriers around the probe which are produced mainly by the photoelectron cloud. Near the perihelion of the Helios orbit, the effects of the potential barrier and the photoelectron cloud become dominant:

(1) The energy range of the measured photoelectrons is limited by the potential barrier instead of the spacecraft potential U_S (Fig. 1).

(2) Photoelectrons are observed even at the shadow side of the spacecraft.

(3) The photoelectron current leaving the probe is determined by the barrier, even if the spacecraft potential is negative.

The electric fields in the vicinity of the spacecraft lead to disturbances of the electron distribution to be measured. By means of the potential resulting from the model calculations, the disturbances of a given distribution can be computed and compared with the measured spectra. The example in Fig. 4 shows that it is possible to reproduce the essential effects using theoretical models. Together with the interpretation of the data these models lead to the understanding of the modifications of the plasma by the Helios spacecraft.

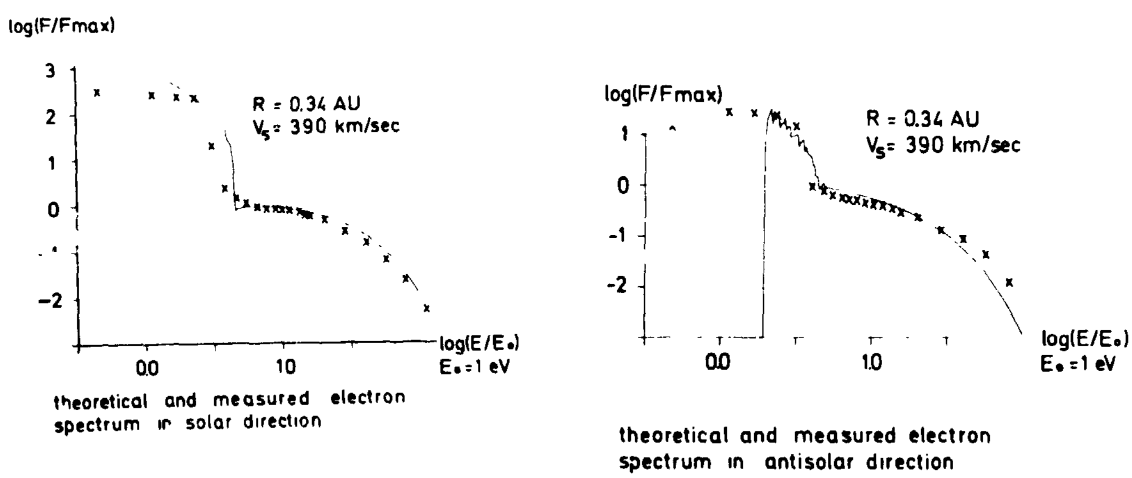

Fig. 4. Comparison of measured (*) and calculated (solid lines) spectra.

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SCIENTIFIC RESULTS OBTAINED BY THE HELIOS TECHNICAL UNIVERSITY OF BRAUNSCHWEIG FLUX-GATE (E 2) AND SEARCH-COIL (E 4) MAGNETOMETER EXPERIMENTS

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A. Brief Description of TU Braunschweig Flux-gate Magnetometer Experiments (E2) on board Helios-1 and -2, and their Scientific Objectives

The flux-gate magnetometer experiments use triaxial, orthogonal flux-gate sensors of the Forster type mounted on a boom of about 2 m from the spacecraft. The bandwidth is 4 Hz. Two measuring ranges are used with automatic range switching. The sensitivity range extends from -100nT to +100nT, with a digitization uncertainty of ±0.2nT for each individual component. The less sensitive ranges extend from -400nT to -100nT and +100nT to +400nT, with a digitization uncertainty of ±0.8nT. The sampling rates extend from 8 vectors per second to 1 vector per minute. For sampling rates not greater than the spin frequency of 1 Hz, The transmitted values have been averaged by an averaging computer which is part of the experiment. The TU-Braunchweig flux-gate magnetometers on board Helios-1 and -2 are still working flawlessly at the present time.

A special feature of the TU-Braunschweig flux-gate magnetometer experiments is the memory mode (also referred to as shock-mode), which allows the rapid read-in of data into a spacecraft memory with sampling rates of 4 or 8 vectors per second. The time intervals are selected by an event detector which is part of this experiment (an alternate event detector is part of Experiment 5b), which has been designed to detect rapid changes in magnetic field magnitude and has been optimized for the detection of interplanetary shocks (by using real interplanetary data in the design phase). The Helios memory mode has produced very interesting results.

The scientific objectives of these instruments can be listed as follows:

(1) study of macroscopic interplanetary magnetic field structure between 0.3 and 1.0 AU also in connection with solar features;

(2) investigation of MHD-waves in the solar wind, particularly of the role of Alfvén waves as the Sun is approached;

(3) study of discontinuities in the solar wind, their relation to macrostructure, generation and decay; more specifically, fast and slow shocks, tangential and rotational discontinuities;

(4) study of the fine structure of shocks and other discontinuities at kinetic time and length scales in conjunction with the higher-frequency search-coil magnetometer and electronic field measurements; and

(5) provision of comparative data, particularly to the solar wind, particle and wave experiments.

B. Brief Description of TU-Braunschweig Search-coil Magnetometer Experiments on board Helios-1 and -2 and their Scientific Objectives

Both experiments use a system of triaxial, orthogonal search-coil sensors of special design aimed at very low background noise levels. The basic output of each sensor is proportional to the time derivative of the magnetic field and they are, therefore, particularly suited for high-frequency observations. The bandwidth of the instrument extends from about 4 Hz to 2.2 kHz to also include R-mode, or whistler mode, signals close to the Sun (0.3 AU). For the reduction of the high basic data rate, the data are generally first processed in a spectrum analyzer. The outputs from the Z-axis (parallel to the spin-axis) and one of the spin plane components X or Y pass through eight logarithmically-spaced analog filters (3 per decade). In a subsequent digital mean-value computer, mean square signals, are computed and peak values are detected for time intervals ranging from 1.125 sec to 20 minutes, depending on telemetry bit rate. In addition, waveform data can be stored in the "shock-memory" at rates of 75, 150 and 300 vectors per second--a particularly scientifically useful capability.

The scientific objectives of the instrument are investigation of:

(1) the role of whistler-mode waves in the solar wind in relation to stream strucure. Also, investigation of ion cyclotron waves near 0.3 AU;

(2) the role of above electromagnetic wave modes in shaping solar wind particle distribution functions, which is a fundamental problem of solar wind plasma physics;

(3) use as a diagnostic tool for particle distribution functions; and

(4) instabilities in thin structures such as shocks and other discontinuities.

C. Highlights of Scientific Results Obtained at the Technical University of Braunschweig using the Helios-1 and -2 Flux-gate and Search-coil Magnetometer Experiments (E2 and E4)

(1) First investigation of radial variation of the interplanetary magnetic field between 0.3 and 1.0 AU (E2; 4).

(2) Macroscopic geometry and fine structure of magnetic sector boundaries using triangulation analysis and local normal determinations. Analysis of associated wave fields (E2, E4; 7,10).

(3) High-frequency electromagnetic waves generated by instabilities in the transition layers of tangential and rotational discontinuities. It has, for example, been shown that most of these discontinuities are associated with peaks in whistler mode wave activity, probably driven by the currents in the discontinuity. Since for a number of cases high time resolution waveform data have been available using the shock-mode, some wave events could be analyzed in detail; i.e., the polarization could be determined leading to the identification as whistler mode waves, the waves could be transfomed into the plasma rest frame, etc. An example of a wave train observed <u>in</u> a tangential discontinuity is shown in Figure 1 (E2, E4; 3,8).

(4) Whistler-mode wave spectra as a function of distance from the Sun (0.3 to 1.0 AU), and in relation to stream structure (E2, E4; 5).

(5) Occurrence properties in relation to streams and energy fluxes of Alfvén waves in the solar wind between 0.3 and 1.0 AU. Alfvén waves, particularly in the inner solar system, are of potential interest because they possibly drive the solar wind. Interesting results on the relative importance of Alfvén wave energy flux relative to the bulk solar wind energy flux are shown in Figure 2 for the primary missions of Helios-1 and -2 (E1, E2, E4; 9).

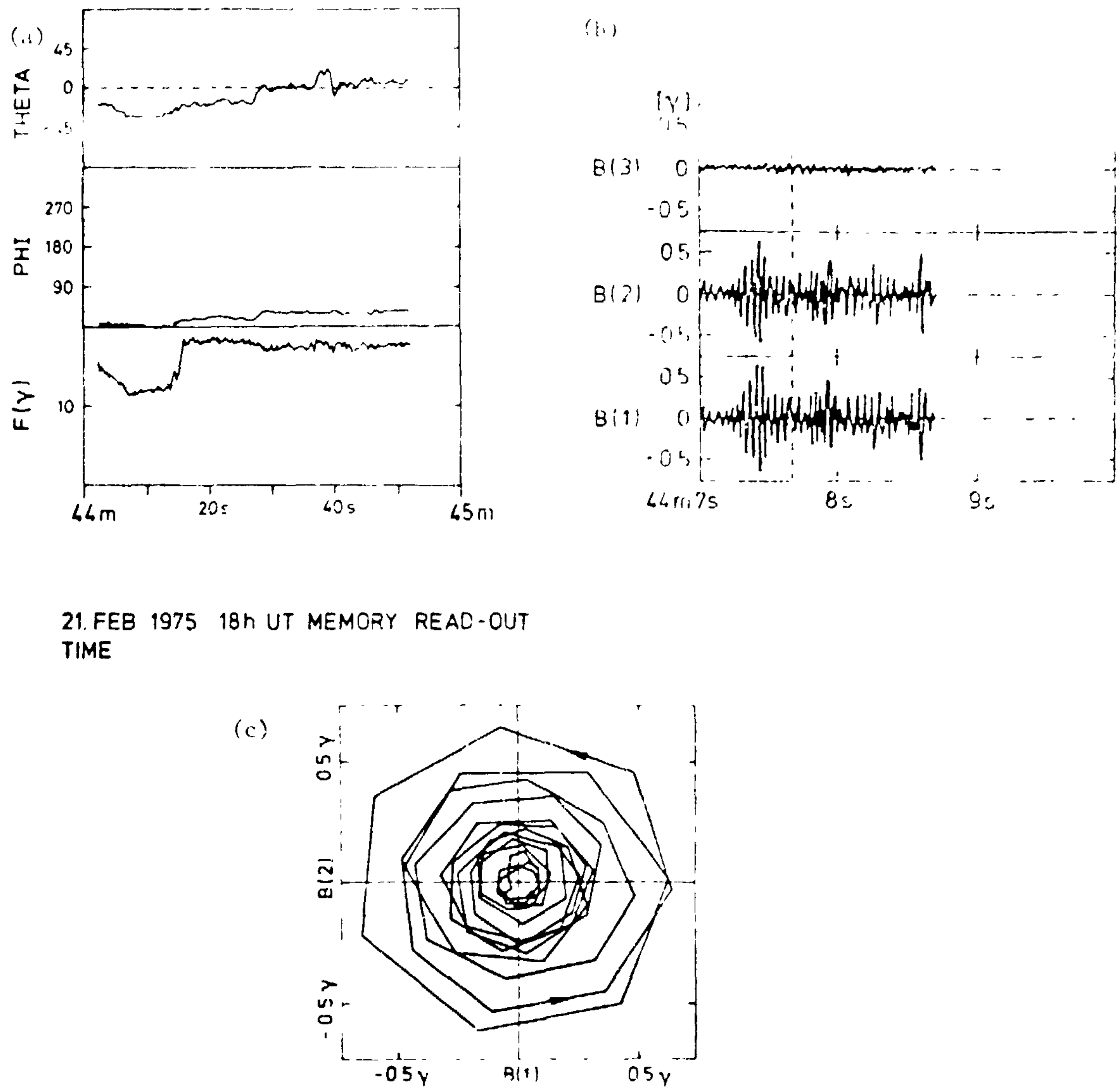

Fig. 1. High time resolution waveform magnetic field data (TU Braunschweig search-coil) obtained in memory mode. Analysis of the wave train leads to observed frequency of 20 Hz; angle between wave vector k and velocity v, 32°; angle between k and magnetic field b, 115%; frequency in plasma rest frame 5.8 Hz.
(a) Flux gate magnetic vector data in solar-ecliptic coordinates.
(b) Search-coil waveform data at 75 vectors/second.
(c) Hodograph of waveform data.

(6) Studies of the fine structure of shocks and associated whistler-mode wave fields. Here the solar wind is used as a plasma laboratory to study the kinetic structure of collisionless shocks. The possibility of studying shocks inside 0.5 AU adds two advantages (compared to studies near 1 AU): The wave

spectral density levels are much higher and shock propagation conditions which are uncommn are sometimes found near 1 AU (E1, E2, E4; 3,5,11).

(7) Multipoint studies of shock propagation in the solar wind between 0.3 and 1 AU (up to 1.6 AU in a joint Helios-Voyager workshop).

(8) Comparison of magnetic field and plasma observations between 0.3 and 1 AU, and Faraday rotation observations at several solar radii with model predictions of three-dimensional MHD models of the solar wind (E1, E2, Faraday rot.; 6).

(9) Study of MHD properties of tangential and rotational discontinuities in the solar wind (E2, E4; 8).

Only those research results culminating in published or submitted papers have been included. A paper on the Helios-Voyager workshop (Item 7), containing major contributions by Helios experiments E1, E2, E3, E5 nd E8 will

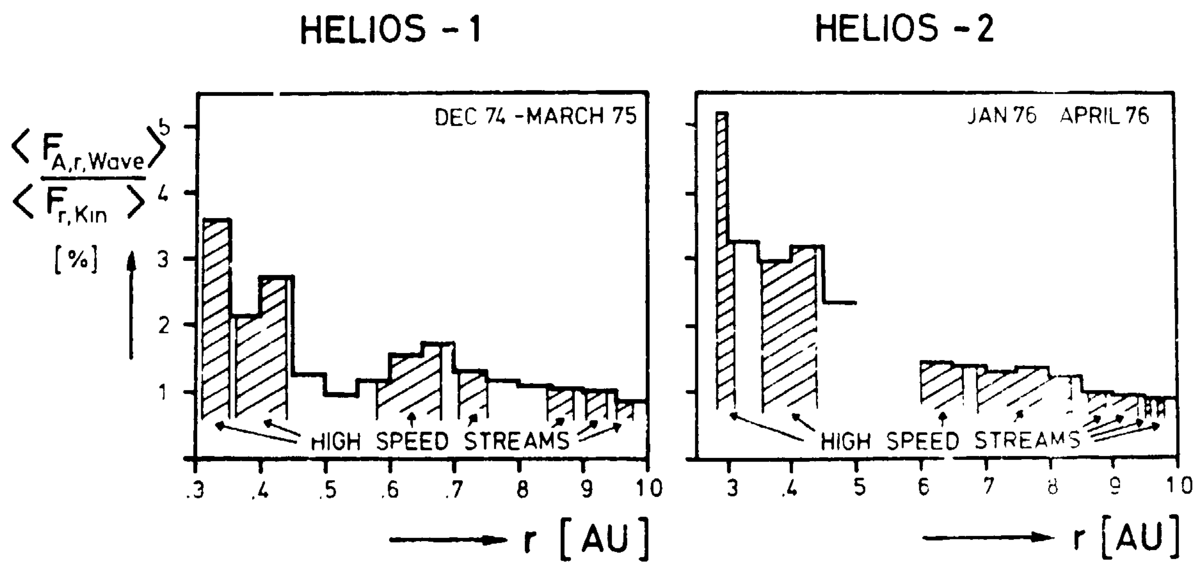

Fig. 2. Alfvén wave energy flux relative to solar wind bulk energy flux as a function of distance from the sun. Note the appreciable Alfven wave energy flux at perihelion of Helios-2 in April 1976.

be submitted for publication in June 1979 by L.F. Burlaga, Goddard Space Flight Center. The numbers in brackets refer to the list of references, including papers published or in press. In addition to these papers, a considerable number of progress reports and invited talks have been given at national and international conferences (IAGA, COSPAR, AGU, EGS).

Further research on new aspects of solar wind physics, as well as the items listed above, is in progress.

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ROME-GSFC MAGNETIC FIELD EXPERIMENT (E 3)

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A. Experiment Description

The Rome-GSFC magnetic field sensor is a tri-axial, fluxgate (saturable inductor) magnetometer. Vector magnetic field measurements are made at equal time intervals at rates ranging from 16 per second to 1 per second, depending on the telemetry bit rates. At low bit rates ($\leq$ 128 bps) the magnetic field is sampled once per spacecraft revolution (1/second), and a number of samples (N) are processed by an on-board computer that calculates the averages of each of the three components of $\underset{\sim}{B}$ and the sum of the variances of the three components. The instrument has four ranges to obtain maximum resolution.

The sensor is mounted on the end of a boom 4 meters from the spin axis, to avoid contamination of the measurements by magnetic fields generated in the spacecraft. The sensor package is provided with a "flipper" which rotates the sensor by 90^{o} so that the zero-levels on the three sensors can be determined. The package is designed with an active thermal control to compensate for the change of solar energy from 1 to 0.3 AU.

The purpose of the experiment is to determine (1) the structure and temporal variations of the interplanetary magnetic field between 1 and 0.3 AU, (2) the nature of the configurations and fluctuations, by relating magnetic field measurements to plasma observations, (3) the sources of the magnetic fields, by relating them to solar observations and (4) the magnetic field configurations and waves that influence energetic particles.

B. Highlights of Results

The analysis of observations is still at an early stage and much remains to be discovered. Nevertheless, a number of significant results have been obtained; some of these are listed and discussed below.

(1) The radial variation of the interplanetary magnetic field between 1 AU and 0.3 AU is in good agreement with Parker's Theory.[2,3] The theory predicts that the radial component of $\underset{\sim}{B}$ should vary as r^{-2}, while the azimuthal component should vary as r^{-1}. Helios-1 observations showed that $B_r \sim r^{-(1.9\pm0.1)}$, and $B_\phi \sim r^{-(1.2\pm0.1)}$ in slow flows while $B_\phi \sim r^{-(1.1\pm0.1)}$ in fast flows. Observations from other deep space probes had suggested that B_ϕ falls off significantly more rapidly than r^{-1}, but recent Pioneer 10 and 11 results are more consistent with Helios results.

(2) The variance of fluctuations in the components of $\underset{\sim}{B}$ varies with r as $\delta B^2 \sim r^{-3}$ consistent with undamped Alfvén waves.[2,3] This implies that Alfvén waves do not appreciably contribute to heating or accelerating the solar wind between 1 and 0.3 AU. However, much remains to be learned about these waves from the Helios data, and further developments in the theory are needed.

(3) Magnetic fields in recurrent streams observed by Helios-1 were shown to originate in coronal holes in which the intensity of open magnetic field lines was 10 to 20 gauss.[4] This confirms results found earlier using data from 1 AU, but the Helios results are significant because they are less subject to uncertainties in projecting data back to the sun. Helios-1 passed directly over a coronal hole at its first perihelion.

(4) Using Helios-1 magnetic field (E3) and plasma observations of a sream near perihelion as inner boundary conditions for an MHD model, it was shown that magnetic fields can play an important role in stream dynamics.[4,7] Prior to Helios, the magnetic field was neglected in most stream models. The Helios results show that this is not justified. A consequence ot magnetic fields is that the interaction regions of steep streams get broader with increasing distance from the sun, rather than narrower, as previously believed.

(5) The shape of a sector boundary surface was measured for the first time by Helios-1 and -2, and was found to be approximately a plane inclined ≈ 10^{o} to the solar equatorial plane with small ripples on it.[8]. This new method of studying sector boundaries in stationary flows is possible because Helios rapidly samples 15^{o} in latitude at each perihelion, and because there are times when Helios 1 and Helios 2 differ in latitude by ≈ 15^{o}. The Helios results are consistent with the reported disappearance of sector structure in Pioneer 11 data at latitudes greater than 16^{o} at the time the Helios observations were made.

(6) A new kind of magnetic field configuration, called a cold magnetic enhancement (CME), was identified.[4] This is characterized by relatively intense magnetic fields in anomalously cold, slow flow regions ahead of fast streams. They have subsequently been identified in data obtained at 1 AU. The origin of CME's is unknown.

(7) Magnetic fields in slow flows were shown to be non-uniform in intensity and direction, and variable from one rotation to the next.[6] These results provide clues to the nature of the source of slow flows, suggesting possibly many small sources.

(8) Magnetic "neutral" sheets have been identified and the structure of some (but not all) of them is consistent with the occurrence of the non-linear, tearing mode instability.[5] These observations suggest, but do not prove the occurrence of the tearing mode. They are significant because the tearing mode can change the topology of the magnetic fields.

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A SUMMARY OF PROGRESS IN SPACE PHYSICS MADE WITH HELIOS PLASMA WAVE INSTRUMENT DATA (E 5a)

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Many significant advances in the study of plasma waves in the solar wind have been made with data from the University of Iowa Plasma Wave Instruments on Helios-1 and -2. The first observations of intense electron plasma oscillations associated with Type III solar radio bursts were made with data from these instruments. These observations confirmed the basic electron plasma oscillation mechanism proposed by Ginzburg and Zheleznyakov in 1958 for the generation of the Type III solar radio emissions. A study of electron plasma oscillation events associated with Type III solar radio bursts, using data from Helios-1 and -2, IMP-6 and -8 and Voyager 1 and 2, found that these events showed a pronounced increase in both intensity and frequency of occurrence with decreasing heliocentric radial distance. Only the Helios spacecraft, with their close approaches to the Sun, have been able to provide in situ measurements of these events in the region of their highest occurrence.

The Type III solar radio burst itself has been studied extensively using data from the Helios spacecraft. Stereoscopic radio direction-finding measurements from the Helios-1 and -2, IMP-8 and Hawkeye 1 spacecraft were used to track a Type III solar radio burst in three dimensions, independent of modeling assumptions concerning the emission frequency as a function of radial distance from the Sun. By combining these radio direction-finding measurements with direct in situ measurements of the solar wind plasma density near the Sun, it was found that the dominant emission occurs at the second harmonic, 2 f_p^-, of the electron plasma frequency. The results of this study confirmed earlier results by other investigations which had to rely on assumed models for the radial dependence of the emission frequency or on average statistical properties of the solar wind.

Further work has also been done on the association of Type III solar radio bursts and electron plasma oscillations in order to provide important new information on nonlinear plasma processes of considerable current interest. A study of the volume emissivity of Type III solar radio bursts showed that although the emissivities varied over a large range, all the emissivities decreased rapidly with increasing heliocentric radial distance. The best fit power law for the events analyzed found the emissivity J proportional to $R^{-6.0\pm0.3}$. When the observed electron plasma oscillation intensities and variation with radial distance (E was proportional to $R^{-1.4\pm0.5}$) were used in two current models for the conversion of electrostatic plasma oscillations to electromagnetic radiation, the observed emissivities were shown to be in good agreement with the predicted emissivities.

The most commonly occurring plasma wave detected by Helios is a sporadic emission between the electron and ion plasma frequencies. These waves are thought to be ion acoustic waves which are Doppler-shifted upwards in frequency from below the ion plasma frequency by the motion of the solar wind. Wavelength measurements from IMP-6 support this conclusion. Comparison of Helios results with measurements from this Earth-orbiting spacecraft show that the ion acoustic wave turbulence detected in interplanetary space has characteristics essentially identical to those of bursts of electrostatic turbulence generated by protons streaming into the solar wind from the Earth's bow shock. In a few cases, ion acoustic wave enhancements have been observed in direct association with abrupt increases in the anisotropy of the solar wind electron distribution. Comparisons with the overall solar wind corotational structure show that the most intense ion acoustic waves usually occur in the low-velocity regions ahead of high-speed solar wind streams. Of the detailed plasma parameters investigated, the ion acoustic wave intensities are found to be most closely correlated with the electron-to-proton temperature ratio, T_e/T_p, and with the electron heat flux. Investigations of the detailed electron and proton distribution functions also show that the ion acoustic waves usually occur in regions with highly non-Maxwellin distributions characteristic of double-proton streams. Two main mechanisms, an electron heat flux instability and a double-ion beam instability have been studied as possible generation mechanisms for the ion-acoustic-like waves observed in the solar wind.

Plasma wave turbulence associated with interplanetary shocks has also been studied using the Helios plasma wave data. Three types of plasma waves are usually detected in association with a strong interplanetary shock: (1) electron plasma oscillations, (2) electrostatic ion-acoustic or Buneman mode turbulence from about 1 to 30 kHz and (3) whistler-mode magnetic noise. The primary burst of electric and magnetic field noise at the shock occurs a few seconds after the jump in the magnetic field, with a broad maximum in the electric field intensities at a few kHz and a monotonically decreasing magnetic field spectrum below about 1 kHz. Many of the characteristics of strong interplanetary shocks are found to be closely similar to previous observations of plasma wave turbulence associated with the Earth's bow shock.

The Helios-1 and -2 Plasma Wave Instruments continue to operate satisfactorily and are returning valuable scientific data. As solar maximum approaches, the number of solar radio bursts and interplanetary shock waves detected has increased dramatically. This increase in activity provides many valuable opportunities for correlative studies with ISEE-1, -2 and -3 to provide triangulation measurements of Type III solar radio bursts and other plasma wave events. Current research efforts are concentrating on the study of plasma waves associated with interplanetary shocks using a large number of events to investigate the dependence of the plasma wave intensities on the Mach number, magnetic field direction and shock normal angle. Other studies of electron plasma oscillations associated with Type III solar radio bursts and electron plasma oscillations and ion acoustic waves in the solar wind are continuing.

ELECTRIC FIELD EXPERIMENT (E 5b)

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Experiment 5b for Helios consists of two parts: (1) a high-frequency resolution (therefore, low temporal resolution) sweeping receiver which measures plasma waves in the frequency range 10 Hz to 200 kHz in 168 channels and (2) a waveform sampler which samples the waveform on the electric antennae and whose purpose is to measure the potential of shocks and of other transient phenomena, as well as to attempt to measure the DC electric field in the solar wind.

The principal result from the sweeping receiver which has been obtained so far is what we consider to be a definitive answer to the problem of whether Type III bursts are primarily generated at the fundamental or at the second harmonic of the local plasma frequency. We found four Type III bursts with Helios-2 which were sufficiently strong enough that we could obtain good spectra. Three of these bursts (the first three found) form the subject of a paper published in the March 1980 Astrophysical Journal. By tracing the onset time of the Type III bursts at each frequency and its intersection with electrostatic plasma waves generated locally at the spacecraft, one can determine that for two of these bursts the initial radiation was at the fundamental of the plasma frequency, while for the third, the onset was in radiation at the second harmonic when the Type III burst was close to the Sun but switched over to the first harmonic as it approached the spacecraft. Similar effects have been suspected by other workers (Alvarez and Haddock), but the switchover was in the opposite direction and at higher frequencies. In any case, the evidence obtained with Helios is quite conclusive.

Most of the phenomena which we see in the solar wind are not highly structured in frequency, so a more modest frequency resolution would have been adequate. One other phenomenon, however, which does show very sharp frequency structure is the ion acoustic noise which Experiment 5a has found to be such a prevalent feature of the solar wind. We have found that the frequency spectrum of this ion acoustic noise has a very sharp high-frequency cutoff. These cutoffs can be understood on the basis of Gurnett and Scarf's high time resolution spectra (from Voyager) as being the highest frequency of a burst which is shaped like an upside-down U on a frequency-time plot. Because of our low time resolution, we do not have as good statistics on ion acoustic noise as Experiment 5a; however, we have found about 15 events with Helios-2 which are suitable for analysis. These have been analyzed and will be published with other not-yet completed work on ion acoustic noise.

The waveform sampling portion of our experiment suffered greatly from photoelectric effects on the antenna potential which greatly limited our sensitivity. We had not understood exactly what would be the nature of the voltage induced on the antenna by the competition between photoelectric emission and plasma electron pickup before the flight of Helios, and a paper entitled "The Potential of an Antenna on a Rotating Spacecraft," discussing our findings, has been submitted to the Journal of Geophysical Research. In this respect, we find that the interference of the solar array is less than the inescapable interference of the photoelectric effect as the spacecraft turns, at least for frequencies below about 100 Hz.

RADIO ASTRONOMY EXPERIMENT (E 5c)

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The Helios Radio Astronomy experiment is designed to track traveling solar radio bursts over the frequency range 2 MHz to 30 kHz corresponding to heliocentric radial distances of 0.1 to 1.0 AU from the Sun. Since the energetic solar electrons responsible for Type III or "fast drift" solar radio bursts travel outward along open magnetic field lines from the source region at the Sun and through the interplanetary medium, tracking these radio bursts provides a unique means of studying the large-scale magnetic field topology and electron density distribution in three dimensions for the interplanetary medium out to at least 1 AU. Helios-2, with a single spinning dipole, can provide only the radio source azimuth angle. Previously, we reported only one case of simultaneous observations between Helios-1 and -2. With these observations we were able to investigate the electron density distribution, as well as the directivity of the radio emission. However, the motion of the source out of the ecliptic, and, thus, the magnetic field configuration out of the ecliptic, could not be uniquely determined with the two Helios spacecraft. Combined with the "tilted dipole" observations with ISEE-3, the radio source position is now being uniquely fixed through triangulational observations with the two spacecraft. Additionally, despite some EMI problems with Helios, the number and intensity of Type III events has dramatically increased as solar maximum is approached.

Thus, for the first time, we are obtaining truly unique "snapshots" of the large-scale magnetic field topology and electron density distribution in three dimensions. Figure 1 shows an example reported as part of invited talks at the IAU symposium "Radio Physics of the Sun" at the fall AGU (1979). The triangles show the trjectory projected into the ecliptic and is seen to be a spiral. The numbers alongside the triangles are the observed source latitude. The associated flare occurred at S19^{o}, W82^{o}. Therefore, the radio source and field lines started at S19^{o}, were at S5^{o} at about 1/4 AU, crossed the ecliptic at 1/2 AU and remained at northern latitudes.

Figure 2 shows the electron density derived for this same event. Large deviations in the electron density distribution from a simple power law are often observed, as in this case. Approximately 50 Type III bursts suitable for this type of analysis have been simultaneously observed by Helios-2 and ISEE-3. A preliminary analysis of some of these events has clearly shown large meridional variations in the magnetic field configuration, as well as large deviations of the electron density gradient from a simple power law distribution.

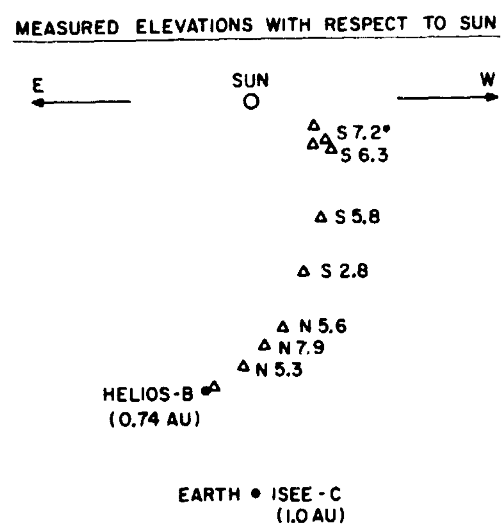

Fig. 1

Until the sucessful launch of the ISPM mission (1983--85) and the subsequent two spacecraft's wide separation (1985-87), the current Helios-ISEE-3 observations provide the only method of remotely observing the large-scale field topology out of the ecliptic.

We are also investigating, again through joint Helios-ISEE-3 observations, the occurrence of Type II or slow drift traveling solar radio bursts excited by solar eject. induced shock waves.

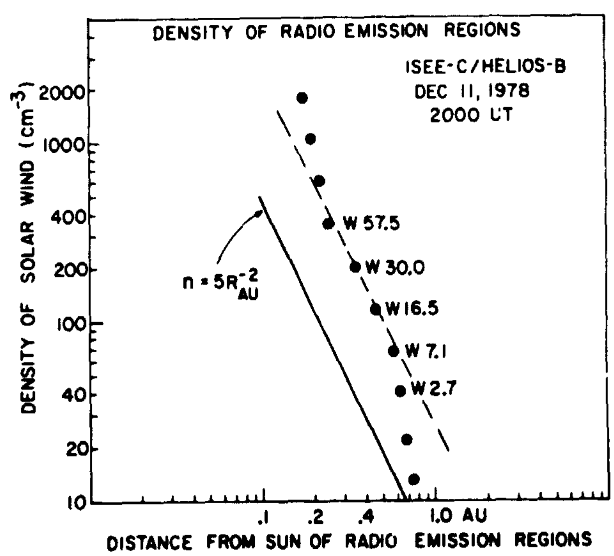

Fig. 2

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COSMIC RAY EXPERIMENT (E 6)

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The cosmic ray particle instrument consists of a detector telescope containing five semiconductor detectors of increasing thickness, a sapphire Cerenkov detector surrounded by an anticoincidence scintillation detector, and an on-board data handling system.

The instrument is capable of measuring protons and heavier nuclei from 1.7 to $\geq$ 400 MeV/n and MeV electrons. It is designed to provide good energy and charge resolution from measurements of individual particles which are selected by a priority scheme. In addition, isotopes of Hydrogen and Helium can be separated. For higher time resolution and for the determination of the angular distribution using eight sectors, the total number of valid particles is accumulated in 96 counting channels which represent in most cases protons, heavier nuclei or electrons of larger energy ranges.

The primary objectives of the instrument are the investigation of the cosmic ray propagation in the inner solar system (solar cosmic rays and modulation), investigation of the coronal propagation of solar flare-generated particles, and studies of the effects of interplanetary shock fronts on the particles. This is performed by measuring energy spectra, chemical and isotopic composition and pitch angle distribution, and their spatial and temporal variation during solar events, corotating events, Jovian electron observations, energetic storm particle events and for galactic cosmic rays during quiet times.

A. General

The advantages of the Helios-1 and -2 missions for cosmic ray studies can be characterized by the following features:

(1) The inner solar system between 0.3 and 1.0 AU can be probed repeatedly during varying conditions of solar activity. The long active measuring period of the two spacecraft covers the declining phase of the preceding solar cycle, solar minimum conditions, the rising phase of the new cycle, and, hopefully, the period up to the next solar maximum.

(2) The closer approach to the Sun allows studies during solar flare events related to the acceleration and release processes which are not detectable from 1 AU and beyond, because here effects of interplanetary scattering smear out details of processes occurring close to the Sun. In addition, small solar events--which are interesting in many respects--can be resolved with better statistics.

(3) The existence of two spacecraft which are, in general, at different heliocentric radial distance, longitude and sometimes latitude allows separation of coronal and interplanetary propagation effects. Ideal situations exist during periods of magnetic lineup with spacecraft near the Earth and in outer space.

(4) The excellent coverage of Helios-1 and -2 from the DSN and other antennae, combined with the data storage capabilities, has provided unique data coverage during most of the lifetime of the two space probes.

(5) The combination of "particles and fields" experiments on Helios, in particular the relation between cosmic rays, magnetic fields and interplanetary plasma, and the existing and continually-growing cooperation between the various experimenters are prerequisites for the new results which were obtained.

(6) The angular resolution of the Kiel experiment and the range of particle types and energies measured allows us to study the full set of problems related with energetic particles in the solar system. These problems, and the results obtained so far, are briefly summarized in the following sections.

B. Solar Cosmic Rays I: Interplanetary Propagation

The full spectrum of various interplanetary propagation models (nearly scatter-free, coherent, focused transport diffusion) has been found in the Helios data. Several cases with an extremely small amount of interplanetary scattering could be identified. Figure 1 shows the result of cooperation with the Caltech group for the March 3, 1975, event when Helios-1, at 0.4 AU, and IMP-8, at 1.0 AU, were located on nearly the same interplanetary magnetic field lines. The change in absolute intensities, the temporal shift and the long-lasting anisotropies are a clear indication of the coherent mode of propagation. The observed intensity profiles relate directly to the solar injection process (A.10, B.18).

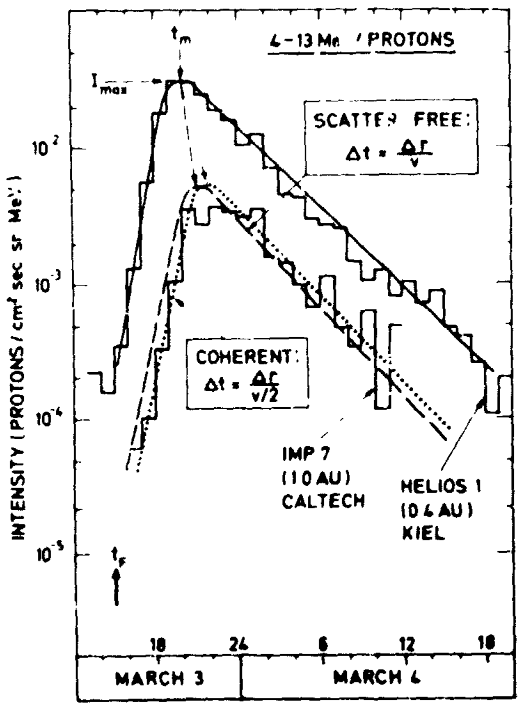

Fig. 1: Intensity time profiles of the March 3, 1975 event, an example of coherent propagation.

During another event, a finite, but large, mean free path of $\lambda = 0.7$ AU is found for both ~ 0.5 MeV electrons and ~ 5 MeV protons. Figure 2 shows a fit of Earl's model of focused transport to the March 28, 1976 event (Helios 2 at 0.5 AU). The solar injection is indicated by the dashed line. The corresponding onset of the relativistic electrons coincides almost exactly with the 7 GHz radio noise burst. Analysis of angular distributions (Fig. 2, top right) allows us for the first time to determine the form of the pitch angle scattering coefficient, which goes through a minimum near 90^{o} pitch angles, but is inconsistent with models of isotropic or Alfvenic wave scattering (A.13, A.17, B.27). The same event is studied by applying the collimated convection models (A.19, B.22). In any case, the great importance of the large-scale interplanetary magnetic field structure is stressed.

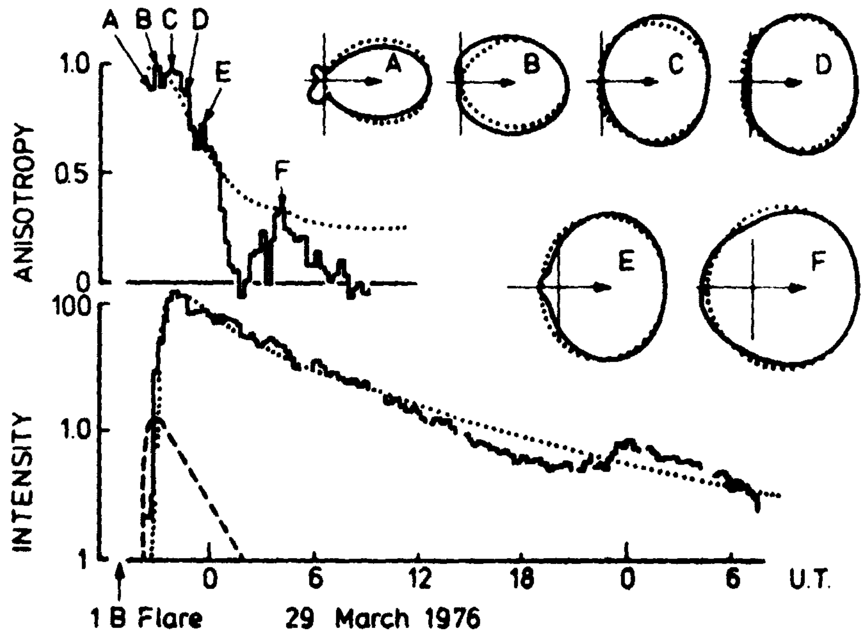

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Fig. 2: Fits of the focussed transport model to intensities, anisotropies and angular distributions.

The systematic study of proton-to-alpha variations during solar events has confirmed the surprising finding that occasionally $\partial\lambda/\partial P < 0$ for rigidities $P \leq 150$ MV, which no existing scattering theory is presently able to explain (B.17, B.28, C.6). The p/α-variation for a number of events is shown in Figure 3 (B.28, C.6).

Apart from the short-lived, highly-anisotropic events mentioned above, we find long-lasting events with nearly isotropic angular distributions. A systematic study is under way to relate the different types of events to the large-scale structure of interplanetary space and to different phases in solar wind streams. Full advantage will be taken of Points (3) to (6) mentioned above. Related theoretical work (A.11, A.14, A.15, A.20, A.21) will aid us in interpreting the variety of experimental results.

C. Solar Cosmic Rays II: Coronal Propagation and Solar Injection.

The different appearances of events when Helios-1 and -2 are at different heliocentric longitudes is immediately obvious in a large number of cases (A.8). The variations cannot be explained by coronal diffusion alone (A.6), but confirm the role of solar sector boundaries as inhibitors for coronal transport. Figure 4 shows the absence of the March 28, 1976, event in the protons on Helios-1, connected with a different solar sector than Helios-2. The appearance of a small remaining electron population presents a puzzle; it indicates that in contrast to the similar propagation of electrons and protons along the interplanetary field, their transverse transport, either in the corona or in space, must be different. For the long-lasting event of March 23, 1976 (Fig. 3) we find a decay time for coronal release of (30±3)h, an e-folding angle for the longitudinal dependence of (40±8)^{o} (A.6, A.16).

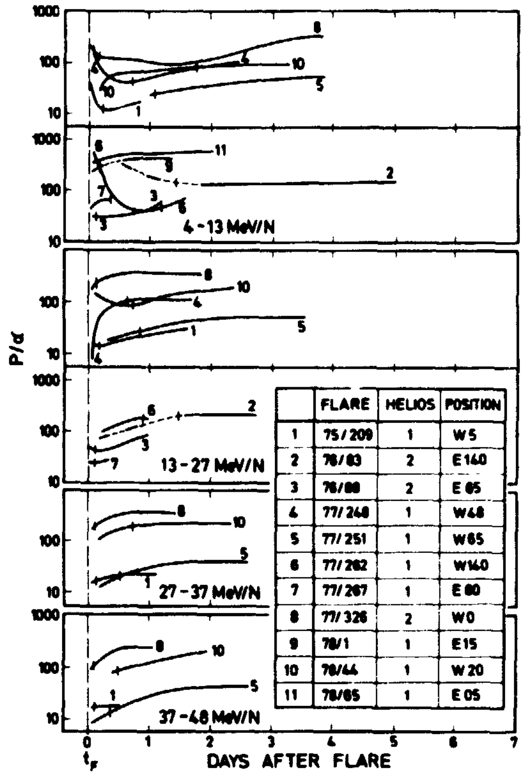

Fig. 3: p/α variation for various energy ranges during several events.

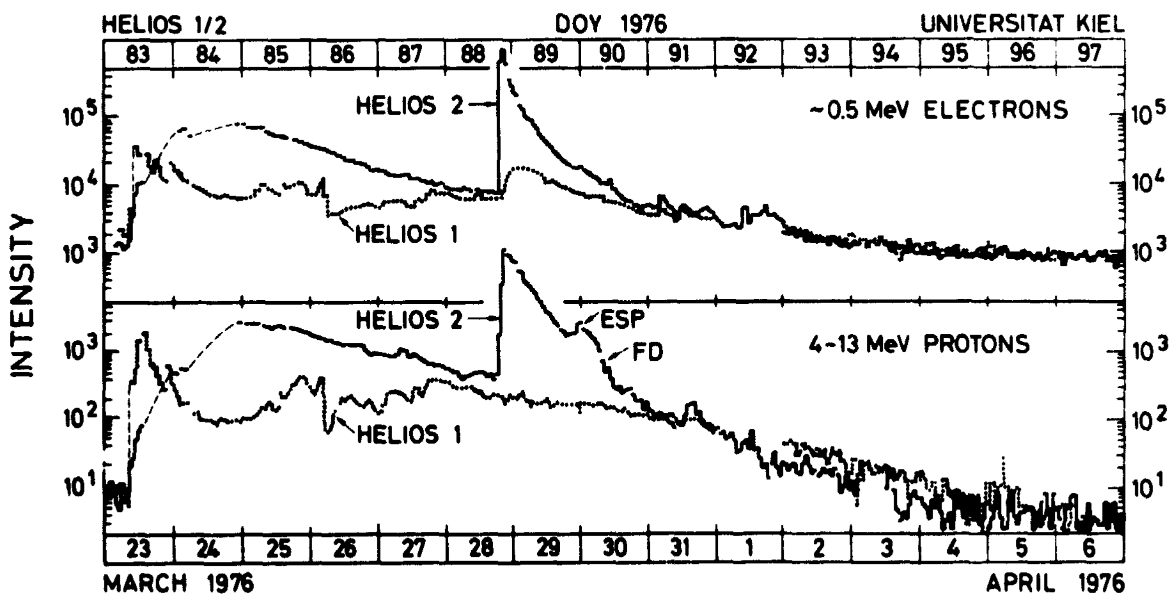

Fig. 4: Intensity time profiles during March 1976.

Clues to the solar injection process for events with small interplanetary scattering have been discussed in Section B (see Figs. 1 and 2).

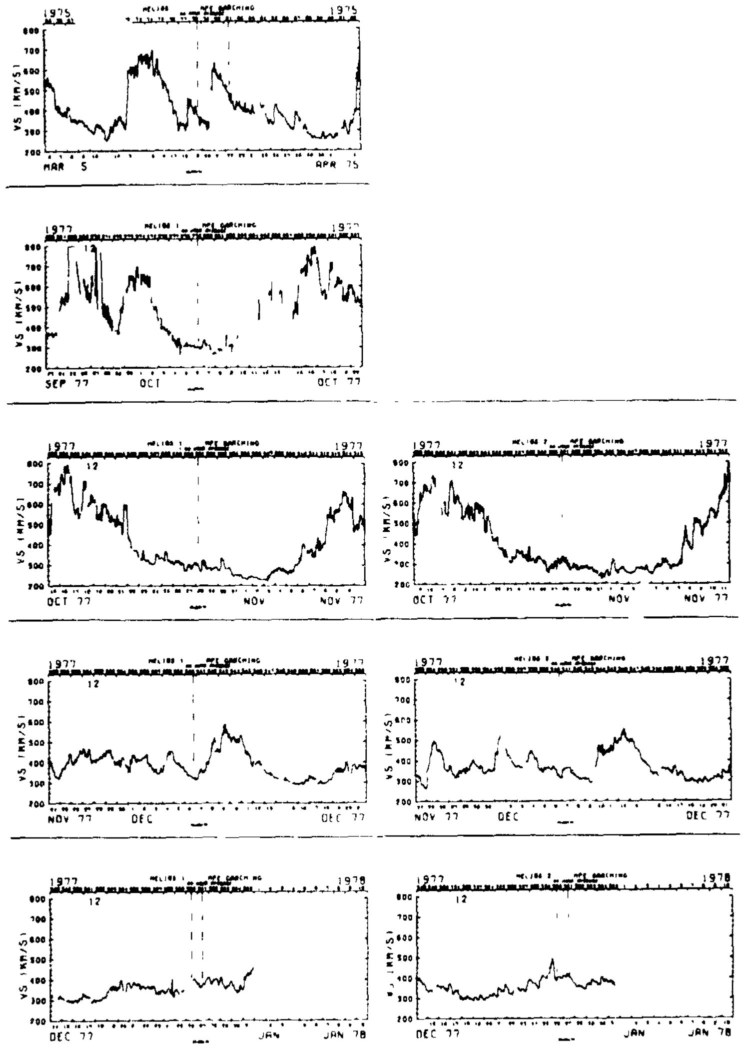

Fig. 5. Relation of ^{3}He-rich events to the solar wind velocity (courtesy H. Rosenbauer and R. Schwenn).

D. Solar Cosmic Rays III; He^3-rich Events

Until December 1977 we had found 9 He^3-rich events with ratios $\Gamma(He^3/He^4) > 0.2$ (B.29, C.7). Earlier findings on this unusual class of solar events have been confirmed (small events, no d and t, large He^4/p-ratio). It is interesting that apart from the nucleonic compositions these events do not seem to differ from "normal" events. They show similar temporal structures and the same ratio of relativistic electrons to ~10 MeV protons. This confirms the idea of preferential pre-heating of He^3 under suitable source conditions followed by the normal flare acceleration process (Fisk, 1978). One unusual feature, which needs confirmation by other events found so far, is the appearance in the slow solar wind (based on plasma data from E1, courtesy H. Rosenbauer and R. Schwenn) (Fig. 5). The event with the largest He^3 content shows a rather peculiar difference between the time profiles of electrons, protons and Helium nuclei, depicted schematically in Figure 6 (A.7, A.10). This is an example of a situation occurring rather frequently, namely that repeated small injections of Helium nuclei are accompanied by much smaller, or even no, increases in protons or electrons (A.10).

E. Interplanetary Acceleration (Recurrent Events)

The first direct gradient measurement during the same recurrent event was obtained by a comparison of Helios-1 and -2 and IMP-7 and -8 measurements in cooperation with the Caltech group (A.9). Figure 7 shows the radial intensity variation between 0.4 and 1.0 AU for the corotating event in March 1976. Numbers 1 through 7 indicate various phases of the event. In the main phase (3 to 7) we find (330±20)%/AU for the radial gradient. The positive value clearly indicates an outer source; interpretation in terms of a stationary diffusive/convective solution (Marshall and Stone, 1977) leads to a radial mean free path of 0.04±0.01 AU, in good agreement with results from solar particle events (A.10).

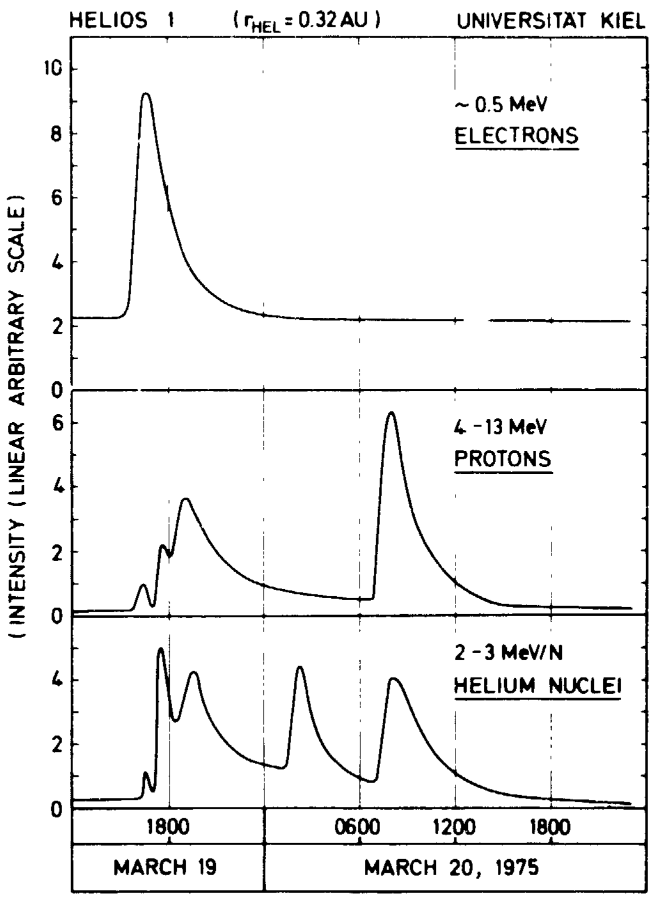

Fig. 6. Intensity time profiles of the ^{3}He-rich events of March 19 and 20, 1978.

The jump to a large positive gradient coincides with a marked increase in the absolute intensity and with the onset of a fast solar wind stream. A more detailed analysis for additional events is presently under way with the aim of revealing the conditions for the occurrence of interplanetary acceleration related to corotating shocks.

F. ESP-events and Forbush-decreases

The study of Energetic Storm Particle (ESP) events gives in situ information on acceleration of charged particles by interplanetary shocks and on the large-scale structure of shock-related magnetic fields. A number of ESP-events detected on Helios show the following signatures: (1) the intensity of MeV protons in the decay phase of a solar event starts well before the shock arrival, (2) the anisotropy increases gradually and changes sign with the shock front and (3) the alpha-to-proton ratio shows different behavior from one event to the other, ranging from no change at all to a factor of 2 increase.

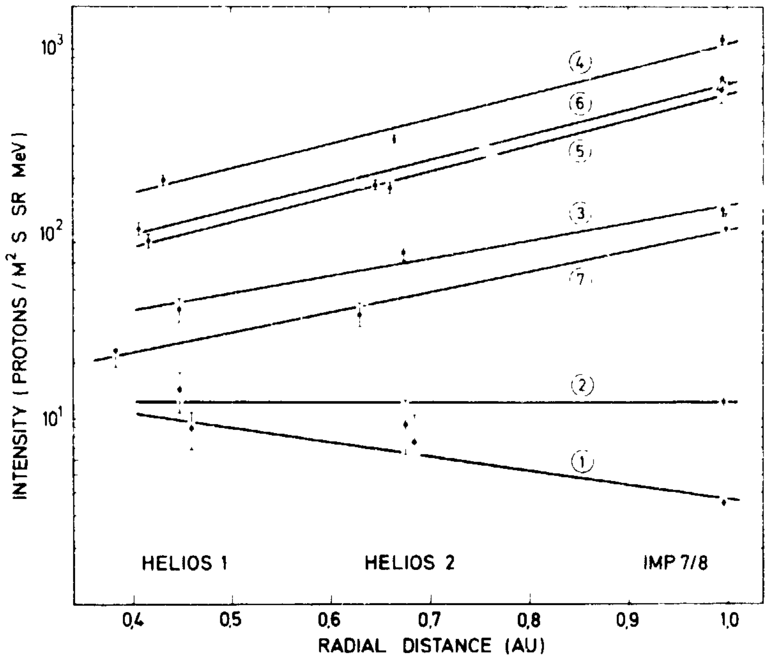

Fig. 7. Radial dependence of the intensity of the March 1976 recurrent event for different phases during the event.

It is interesting that similar signatures are also found during magnetic field enhancements which are definitely not shocks. In many cases, the ESP-event is limited by the arrival of the piston driving the shock. In these cases, the highest-energy channel displays a marked Forbush decrease. The two features seen in the cosmic rays indicate the arrival of large extended magnetic field discontinuities, which act as rigidity-dependent barriers for energetic particle penetration (for first results see B.24, B.25, C.3).

G. Jovian Electrons

The Helios orbits offer the possibility of observing electrons of Jovian origin in the 0.3 to 2 MeV energy range at distances from 1 to 0.3 AU from the

Sun. These data are not contaminated by Earth magnetospheric electrons from which IMP data in this energy range suffer. The time period from launch of Helios-1 in December 1974 to September 1977 was centered around solar minimum and, furthermore, showed exceptionally-low solar activity. This provided excellent conditions to observe the dependence of Jovian electron events on the "Jovian electron seasons" down to 0.3 AU where interplanetary shock fronts, in connection with fast solar wind streams, do not yet develop. This observation favors a model in which the propagation of charged particles, at least in this rigidity range, is governed by the large-scale structure of the interplanetary medium and in which diffusion, especially perpendicular to the magnetic field, does not play a significant role (A.18, B.23, B.26).

H. Modulation: Long-term Changes and Spatial Gradients

During the recovery phase of solar cycle 20 we have observed significant long-term variations in the cosmic ray intensity: While the Deep River neutron monitor readings increased by 2.7% between December 1974 and June 1975, we observe a 50% increase of 30 MeV protons with a phase lag of 2 to 3 months and a 100% increase in the Helium intensity at 30 MeV/n with a phase lag of 1 month; i.e., Helium nuclei are modulated roughly twice as much as protons of the same energy/nucleon.

To determine the radial gradients in the period of pronounced time variations, we have reduced the effects of time variations by using the ratios of the particle intensities measured by the GSFC cosmic ray experiment on IMP-8, kindly provided by T. von Rosenvinge. From December 1974 to December 1975, the proton gradients in the energy range 20 to 50 MeV are small and generally consistent with zero within errors, whereas the Helium gradients are small, but positive (A.7, A.12, B.12).

Scanning the inner solar system four times in 13 months of pronounced time variations did not reveal a clear change in the differential proton and Helium gradients. From this we conclude that the observed long-term intensity variations occurred almost simultaneously and uniformly in the inner solar system, indicating a large distance to the boundary of the modulation region. This allows the Helios measurements to serve as a good baseline for other deep space missions.

The integral gradients for protons and Helium nuclei were determined without a reference measurement at 1 AU, but during a time of only small temporal variations (end of 1977 to beginning of 1978). During this time period, the Helios spacecraft had traversed the space between 1 and 0.3 AU eleven times. A superposed epoch analysis yields gradient values of 20±9%/AU for > 51 MeV protons and 28±12%/AU for > 48 MeV/n Helium nuclei. These large values, observed inside 1 AU, differ from the results of the Pioneer 10 and 11 measurements taken between 1 and 18 AU. They can be explained by a radially-dependent diffusion coefficient, as proposed by Morfill et al. (1979). Comparison with a model of three-dimensional modulation is in preparation.

I. International Cooperation, Future Plans and Interest in the Scientific Community

A rich research program for further investigation of the solar system is still under way. The Helios-Voyager workshop in the fall of 1978 and the Helios Working Group Meeting in the spring of 1979 indicated a large number of interesting solar events, covered by many spacecraft, from the new cycle. Results from the Helios-Voyager workshop have been presented at two conferences (Spring AGU Meeting, 1979; International Cosmic Ray Conference, Kyoto, 1979). Future cooperation on a number of problems has started with the APL/JHU group (Prof. E.C. Roelof), and cooperation with the Central Research Institute of Physics, Budapest, is under way. Hopefully, Helios will survive its next aphelion so that the coordinated efforts during the SMY will supply an unprecedented opportunity for tackling and finally resolving the acceleration and release processes during solar flares.

The great interest throughout the scientific community is documented by invited and public talks. Integration into the University research program is indicated by a number of Master's theses and dissertations (section C, Bibliography).

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COSMIC RAY EXPERIMENT (E 7)

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The purpose of the Helios experiment E7 is to carry out investigations of the energy spectra, charge composition and flow patterns of both solar and galactic cosmic rays. Three separate dE/dx vs. E telescopes, in combination, enable the following particle species and energy ranges to be measured: electrons, 50 keV to ~8 MeV; protons, 100 keV to ~800 MeV; alpha particles, to 600 MeV/nucleon; heavier elements up to Neon to ~200 MeV/nucleon. The experiment includes a proportional counter to monitor solar X-rays in the range 2 to 8 keV with coarse event location on the Sun.

In addition, Helios-2 includes a gamma-ray burst detection system (co-investigators for this portion are T.L. Cline, U.D. Desai and B.J. Teegarden). The instrumentation for the gamma-ray burst system includes a separate sensor with a memory that preserves each gamma-ray burst time history with 4-millisecond time resolution. The purpose of this experiment is to accurately triangulate gamma-ray transient source positions by comparing wave front profiles with other interplanetary and near-Earth sensors.

Introduction

The Goddard Space Flight Center cosmic ray experiments aboard Helios-1 and -2 are used to investigate a number of astrophysical problems ranging from solar cosmic rays to interplanetary acceleration process studies to studies of the galactic and the so-called anomalous component. The broad solar minimum condition which persisted from 1972 to the beginning of 1978 favored some studies such as that of interplanetary energetic particle streams related to corotating interaction regions and that of the radial gradient and the energy spectra of the galactic and anomalous components. Solar cosmic ray studies progressed more slowly, with only a few solar flare events being observed by Helios before late 1977, at which time a few large solar flares were reported from the new solar cycle. A number of the studies described here are still in progress, since the observation of a larger sample of events is necessary to lead to definite conclusions.

A. Solar Cosmic Rays

(1) Intrinsic Characteristics of Solar Flares

One important characteristic in studying acceleration processes is the source energy spectrum. This has been investigated in the past by Van Hollebeke et al. (1975) using data from a large number of events observed at 1 AU. By analyzing the variation of the proton energy spectrum with the azimuthal distance from the flare to the observer connection longitude, these authors found that over the limited energy range from 20 to 80 MeV, the spectrum of the proton number density can be expressed as a power law in kinetic energy ($N(E) \sim E^{-\delta}$ for events associated with flares that are well-connected magnetically to the observing spacecraft. δ has a very small dispersion, with 90% of the events ranging between 2.5 and 3.7. It was further discussed that the effect of interplanetary transport can be neglected, provided this spectrum is determined from measurements made at maximum intensity. Thus, such a measured spectrum could be considered as a good representation of the source spectrum.

From Helios-1 and -2 observations at ~.6 AU of a flare-associated event magnetically well connected, it now appears that over the extended energy range from .3 to 300 MeV the proton spectrum departs slightly from a power law, since it bends at energies below 1 MeV and steepens above 200 MeV. A calculation by Ramaty (1979), using a Fermi acceleration process for the second stage acceleration, gives a very good fit to the data. Figure 1 illustrates this calculated fit (dashed line), superimposed on the measured proton spectrum, for the April 8, 1978, event. To further confirm this study, more observations at close distances to the Sun of events magnetically well connected to Helios are necessary. Due to the increasing number of large flares incoming from the new solar cycle, we expect that a conclusion of this study will soon develop.

(2) Coronal Transport and Particle Release

Evidence of a "fast propagation region," where energetic particles appear to have nearly immediate access to the interplanetary magnetic field over a region extending $\pm 60^{o}$ from the flare site, was found earlier from statistical studies of flare-associated events detected by a single spacecraft observation at 1 AU near the Earth. Observations by Helios-1 and -2, closer to the Sun and at different azimuthal distances with respect to the flare site, of a few flare-associatd events have further confirmed the existence of this fast propagation region. In addition, the fast component, attributed to energetic particles propagating in front of the flare-associated shock, has been identified in the case of the very energetic event of April 28, 1978,when Helios was at .3 AU from the Sun, as a spike occurring just before the main increase of the event. This study, presented at the 16th International Cosmic Ray Conference, is being extended using both magnetic field and anisotropy measurements to determine: (1) the role of the shock in the acceleration mechanism preceeding the release of the particles into the interplanetary medium, and (2) the physical process leading to the release of energetic particles in front of the shock.

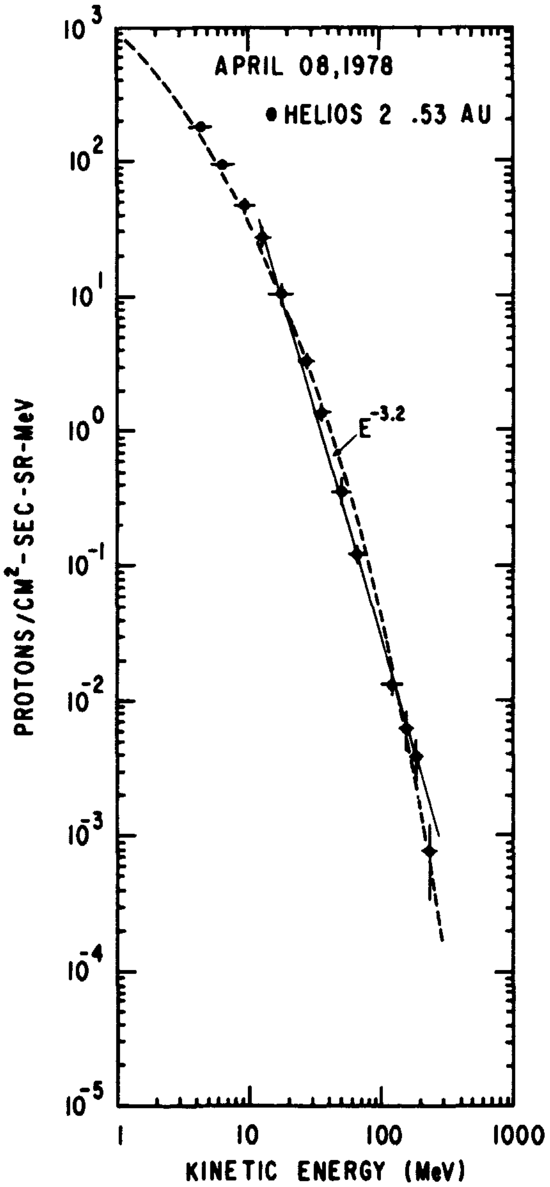


Fig. 1: Source proton energy spectrum observed by Helios-2 at .5 AU. The dashed line is a fit to the data by Ramaty (1979) using a stochastic Fermi-type acceleration during 2nd phase of accel.

Using mainly statistical analysis of observations of a large number of events by a single spacecraft, past investigations of the energy dependence of the release of particles into the interplanetary medium (after their transport in the corona) have been quite controversial. Based on the observed increase of the spectral index away from the flare longitude, and assuming that the coronal propagation is independent of energy, Van Hollebeke et al. (1975) concluded that there was a dependence of energy (or velocity) for the escape rate. However, two similar studies at different energies by McKibben (1973) and Reinhard (1975) did not show any dependence of the slope of the energy spectrum with heliolongitude. Helios-1 and -2 and Voyagers 1 and 2 provided the first opportunity to resolve this apparent discrepancy. The spacecraft longitudes were 120^{o} apart during the observation of a series of solar flares observed in September 1977. An analysis was performed by Conlon et al. (1979) of the variation with the heliolongitude of the spectral shape and of the abundance of alpha particles relative to protons. For this series of flare-associated events, the analysis supports the earlier conclusions of Van Hollebeke et al. (1975). However, the energy spectrum for this series of events is generally harder than that found in the previous statistical analysis of flares detected during the previous solar cycle (see Fig. 2).

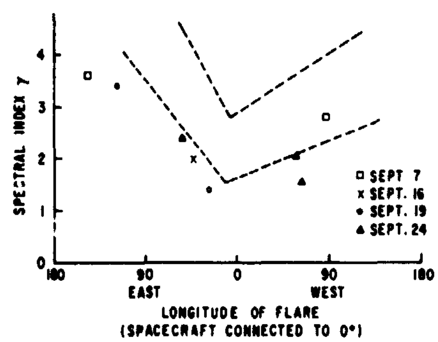


Fig. 2: Variation of the energy spectral index with the flare heliolongitude relative to the observer connection longitude. The data points are observations by Helios-2 and Voyagers 1 and 2 for the September 1977 series of events. The dashed contours refer to the envelope which contained 90% of the events observed during the previous solar cycle and were previously analyzed by Van Hollebeke et al. (1975). (From Conlon et al., 1979).

Preliminary analysis seeems to indicate that this difference may reflect changes in the dynamics of the acceleration process, either for this particular active region only, or for all flares observed during the present solar cycle. This study, which is of great importance to understanding the dynamics of acceleration processes relating to solar cycle, is being pursued on more solar particle events which have since occurred.

B. Corotating Energetic Particle Streams, Interplanetary Acceleration

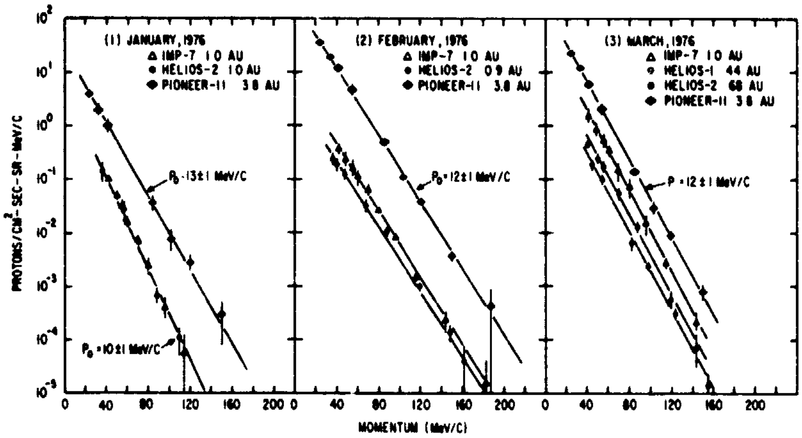
The corotating energetic particle streams are the major source of MeV protons in the outer heliosphere during solar minimum. The discovery of a positive radial gradient by Pioneers 10 and 11 between 1 and 4 AU led McDonald et al. (1976) to propose interplanetary acceleration as the most plausible explanation for the formation of those streams and to suggest the suprathermal distribution of the solar wind as a possible source of particles. To assist in the confirmation of this result and to define the possible type of acceleration mechanism and the origin of the pre-accelerated particles, detailed studies of the main characteristics of these events have been performed. These studies used primarily the network of cosmic ray experiments now available with Helios-1 and -2 (between .3 and 1 AU), IMP-7 and -8 (near Earth, at 1 AU), Pioneer 11 (between 1 and 5 AU) and Pioneer 10 (between 1 and 10 AU) in correlation with solar wind measurements. They covered much of the solar minimum period of Cycle 20 and ranged from .3 to 10 AU.

The main characteristics that such studies have revealed are:

(1) the existence of a positive radial gradient of some +350% per AU between .3 and 1 AU. An average gradient exists of +100% per AU between 1 and 4 AU and a negative gradient of some -40 to -100% per AU beyond 4 to 6 AU. No evidence of a latitudinal gradient for $\theta < 15^{o}$ has been found on the data organized, with respect to heliolatitude.

(2) the close association of those particle events with corotating interaction regions (CIRs) formed between the high-speed and low-speed solar wind streams (as seen by Pioneer beyond 1.5 AU) was found to persist near and inside 1 AU with the energetic particles contained only inside the high-speed solar wind stream, in a region adjacent to the CIR.

The form and the radial dependence of the energy spectrum is of special importance in defining the spatial dependence of the acceleration process. It was found that an exponential in momentum of the form $dJ/dP \propto e^{-P/P_o}$ gives a good fit to the data for both proton and alpha particles. P_o ranges typically from 9 to 16 MV/n for most of the events and shows little variation with radial distance from .3 to 4 AU, while the intensity may vary by more than two orders of magnitude over this distance (see Fig. 3). The variation of the energy spectra with respect to CIR boundaries was also studied. These results, published by Van Hollebeke et al (1978) and Van Hollebeke et al.



<u>Fig. 3</u>: Energy spectra of a corotating energetic particle stream observed for 3 consecutive solar rotations in 1976 (from Van Hollebeke et al., 1979).

(1979), have been used extensively by those and other authors in their approaches to resolve the problems of the origin and interplanetary acceleration of corotating particle streams.

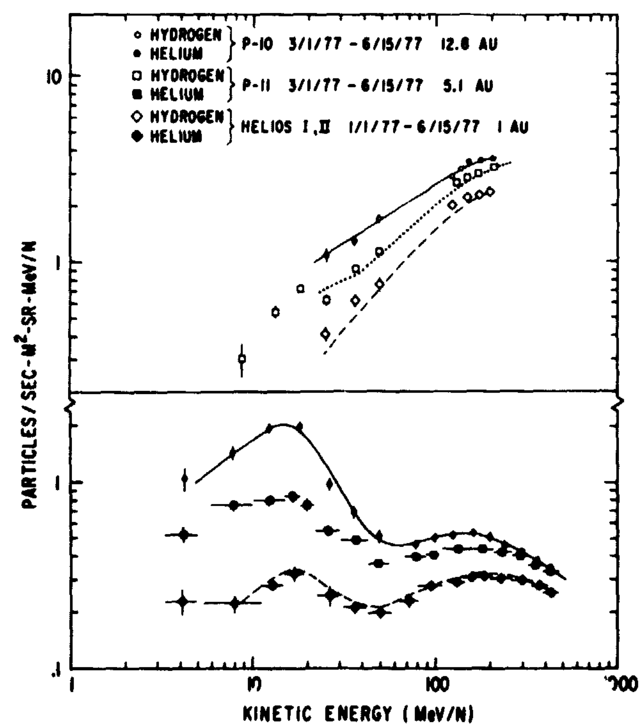
C. Galactic Studies

With essentially identical cosmic ray detector systems (as on Pioneers 10 and 11), the Helios-1 and -2 missions have provided a good baseline for measuring directly the amount of residual modulation near solar minimum when the oserved galactic cosmic ray intensity has its larger value, and at the time when the anomalous component is observed at 1 AU.

In order to determine the radial and rigidity dependence of the modulation, the variation of the energy spectra with radial distance has been measured over the extended range of energy from 5 to 500 MeV/n for alpha particles and from 20 to 56 MeV and 120 to 200 MeV for protons. The periods selected for these studies were late 1975, when Pioneer 10 was between 8.5 and 9.1 AU and Pioneer 11 at ~3.8 AU (McDonald et al., 1977), and from March to June 1977 when Pioneer 10 was ~12.8 AU and Pioneer 11 at 5.1 AU (McDonald et al., 1979).

It was found that the observed gradient decreases with heliocentric distance and that this change varies with energy from a ratio of 4 at 200 MeV to 1.7 at 15 MeV. Such changes suggest that the diffusion coefficient may not be a separable function of position and rigidity.

Above 1 GV the measured gradients of He and H are well described by conventional modulation theory. At low energy the He is dominated by the anomalous component. Observations during the second selected period show that the spectral shapes of Helium at those energies are not greatly changed between 1 and 13 AU (implying reduced energy losses for these particles). In the same manner, the apparent energy loss for low-rigidity Hydrogen appears to be appreciably smaller than expected (see Fig. 4). Those observations led McDonald et al. (1979) to suggest alternate approaches to that proposed by Fisk et al (1974) to explain the anomalous component.



<u>Fig. 4</u>: Energy spectra for Hydrogen and Helium measured by Pioneers 10 and 11 and Helios-1 and -2. The dashed line through the Helios data is a fit of the form $J_{Helios} = J_{11} \exp-(0.17/\beta)$. The dotted line represents the fit $J_{11}=J_{10} \exp-(\eta_\alpha/\beta)$ where η_α is derived from the Helium measurements (from McDonald et al., 1979).

The study of the radial gradient between .3 and 1 AU has been more difficult. In addition to the radial gradient, measurements made by Helios from .3 to 1 AU represent the combined effects of temporal, azimuthal and latitudinal variations; some of these variations are at least a factor of 3 larger than the expected radial variation. The large-scale temporal and azimuthal effects have been eliminated by using the ratio of the particle intensities measured at Helios to that measured by IMPs 7 and 8 at 1 AU, after correcting for corotation effects.

Transient effects, such as low-energy particle events and Forbush decreases associated with solar flares, have been eliminated from the data. The resulting measurements contain both radial and latitudinal gradients and show a gradient of less than 5% per AU for both protons and alpha particles in the range of ~115 to 220 MeV/n. This result was presented at the 16th International Cosmic Ray Conference and seems in disagreement with the measurements of the University of Kiel group. It is presently being reviewed with a more extensive set of data.

D. Gamma-ray Bursts

Gamma ray transients have been successfuly observed with Helios-2 on over 20 occasions during 1976 to 1979. At least six of these events were also detected by the other space probes and Earth satellites forming an interplanetary gamma-ray burst sensor network, including Pioneer-Venus Orbiter, Venera-11 and -12, ISEE-3, Prognoz-7 and the Vela system. Their use as a long-baseline timing array for acurate wavefront triangulation has produced the first precise (arc minute diameter) gamma-ray burst source locations. The first source object identification for a gamma-ray transient was the N49 supernova remnant in the Large Magellanic Cloud, a galaxy outside our own. The 5 March 1979 transient originating there was shown not to be a typical gamma-ray burst, but a new type of cosmic outburst.

The consequences of this discovery should prove to be very important in high energy astrophysics. One recently suggested explanation (Ramaty et al., 1980), taking into account both the great distance of the LMC and the exact details of the observed spectrum of the transient, involves an internal transition in a neutron star, which dissipates its energy with gravitational radiation. If this is a true explanation, the 5 March 1979 transient is the first detected neutron star transition and can be considered the first direct evidence for gravitational radiation.

Studies of source locations of gamma-ray bursts of the classical Vela variety are presently being undertaken with optical and X-ray telescopes. These source fields are presently "empty" sky, not other supernova remnants or other known X-ray emitters.

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SPECTROMETER FOR MEASUREMENTS OF LOW-ENERGY ELECTRONS AND IONS (E 8)

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A. Short Description of the Instrument and Its Primary Purpose

The instrument developed at our institute (weight: 3.5 kg; power: 4.4 W) utilizes an inhomogenous magnetic field for separation of charged particles. Protons (and heavier particles) traverse the magnetic field almost unaffected and are detected in a telescope arrangement consisting of 2 semiconductor detectors (Silicon surface barrier detectors). Electrons are focused and detected by 4 semiconductor detectors. Positrons (if present) will be deflected in the opposite direction and detected there in another detector. The latter one is protected in a telescope arrangement, in order to suppress background. The instrument is almost normal to the spin axis of the probe and detects particles which are coming from an angular range of $\pm 15^{\circ}$ above and below the ecliptic plane and $\pm 10^{\circ}$ in the ecliptic plane. By utilizing the probe spin, measurements are performed in 16 sectors in order to determine the angular distribution of particles.

Their energy is determined by pulse-height analysis of the various detector signals. The energy spectrum of the particles is obtained separately in all 16 sectors. In total, there are 551 different counting rate words (8 bits each, quasilogarithmically compressed) transmitted; in addition, 3 status-indicating and 20 housekeeping words (voltages, currents, temperatures, noise) are transmitted. The shortest sampling time is about 6 seconds. In regular intervals an in-flight calibration is performed, during which, by electrical means, the amplifiers, thresholds and complicated logic are tested.

B. Highlights of Results

(1) Magnetospheric Studies with Helios

Fortunately for both Helios-1 and -2, it became possible to turn on some of the instruments soon after launch, while the spacecraft were still within the Earth's magnetosphere. Using the magnetometer data and our low-energy particle data we were able to investigate the passage of the Earth's magnetopause and magnetosheath more closely. The spacecraft, with its spin axis in the ecliptic plane, traversed the magnetopause at the dusk side closer to the subsolar point than most other spacecraft. From our study we were able to confirm the existence of the energetic electron layer just outside the magnetosphere and also to identify what we call the "ion layer," which is of a similar nature. The data indicate that the particles are streaming away from the subsolar point along the magnetopause, and also that there seem to be two populations present: one which is clearly seen at higher energies with typically flat energy spectra, and another seen only at lower energies with typically steep energy spectra with a similar slope for ions and electrons. It is this particle population which seems to stem from acceleration at the magnetopause through a magnetic merging process. From the intensities we see, we conclude that the energy flux appearing in these lower energy particles, mostly the ions, is consistent with what one would expect from merging. Also, we propose that the acceleration process to be considered essentially brings plasma particles up into the several tens to a few 100 keV energy range. This, on the other hand, would only require acceleration of a minor percentage of plasma particles ($\sim 10^{-3}$), which would not be noticed by plasma measurements.

(2) Interplanetary Studies

The first interesting event seen on Helios occured on January 6, 1975. Here, a shock front passed the spacecraft which considerably affected the low-energy ion population. Using the Helios instrument set we were able to investigate this event very closely so that the particle spectra obtained during this event could be compared with existing models of shock acceleration of particles. Most important in this context was our finding that the application of the Compton-Getting correction at low energies was not only mandatory, but that in order to perform the transformation correctly (and not rely on unproven or simplified assumptions), the energy spectra of ions had to be measured as a function of direction, which we actually do in 16 sectors. We also noticed that most instruments in the low-energy regime are sensitive not only to protons but to heavier ions, as well, which, during fast solar wind conditions, could actually result in comparable contributions to the counting rate.

A study has now been completed in which plasma and magnetic field data have been used to describe a shock. The energetic particle data have been searched to test for the circumstances which essentially allow acceleration of charged particles. The general findings of this study were that particles are only accelerated if the shock propagates almost normal to the magnetic field, and that some particle population has to be present out of which, apparently, the acceleration process works.

A very interesting observation by the two Helios spacecraft was made during the solar flare event in November 1977. (This event was discussed during the Helios-Voyager Workshop, and the results will be published soon.) The two spacecraft, separated by ~25^{o} in longitude, observed the arrival of relativistic particles simultaneously. Different from Helios-2, Helios-1 did not see low-energy particles at all, while at Helios-2, close to the relativistic particles, low energy electrons ($\leq$ 100 keV) arrived in remarkable fluxes. Long after the peak of the relativistic particles, low-energy ions were also observed. This low-energy population was wiped away when the interaction region, preceeding a fast solar wind stream, passed Helios-2. Physical properties of these interaction regions are presently being studied.

Low-energy electrons quite often show, when they arrive at the spacecraft, a remarkable time dispersion effect. We are presently studying whether these electrons are causing electron plasma oscillations which have often been observed. A clear relationship between both has never been established, but has often been suggested.

With solar activity returning abruptly in September 1977, we have now had numerous observations of low-energy particles related to solar flares. Several studies are now under way to investigate those effects.

(3) Possible Results Expected During Solar Maximum

With the rise of the solar cycle, which started almost suddenly in September 1977, the conditions in interplanetary space changed, as well. While during the quiet times interplanetary shocks were a relatively rare phenomenon, their number has since increased, as has the number of times we have encountered low-energy charged particle populations. Thus, during the maximum phase of the solar cycle, we expect to significantly increase the number of examples of shock acceleration of charged particles to be studied, thus to broaden the basis for refining and improving models for acceleration. The frequency of solar flares has also increased so that propagation studies of charged particles in the inner portion of the solar system can be improved. Until now we have seen only a few examples of flare propagation, while the probes were within the orbit of Mercury.

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ZODIACAL LIGHT EXPERIMENT (E 9)

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The experiment consists of three photometers, each measuring the brightness and polarization of the zodiacal light in three wavelength bands: ultraviolet (360 nm), blue (420 nm) and visual (540 nm). On Helios-1 the photometers are directed south of the ecliptic, scanning bands at ecliptic latitudes -16^{o}, -31^{o} and the region of the south ecliptic pole. Helios-2 surveys the corresponding areas north of the ecliptic.

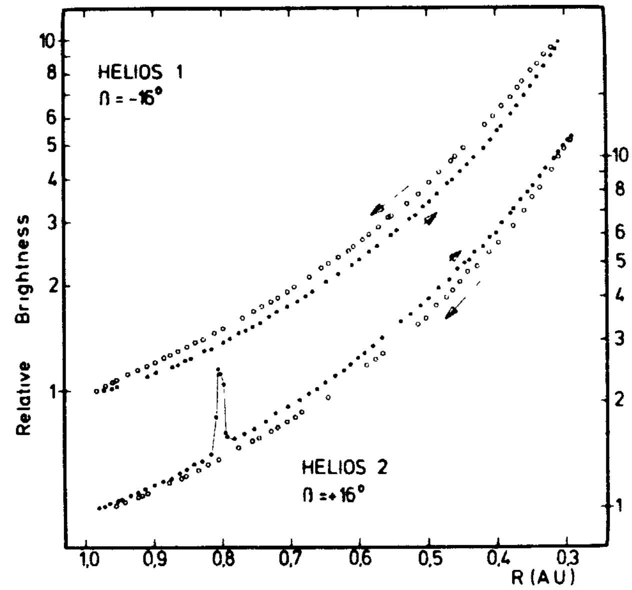
The primary purpose of this experiment is to deduce from the zodiacal light observations the spatial distribution of interplanetary dust within 1 AU.

Results to Date

From the beginning (1) the zodiacal light observations showed a remarkable smoothness and reproducibility. This is illustrated in Figure 1, which shows the average sky brightness as a function of heliocentric distance, as observed by Helios-1 and -2 during one orbit in the first half of 1976. A more detailed presentation of all available measurement during January 1975 for one specific viewing direction is shown in Figure 2. Note that part of the remaining scatter is due to changing star background. Work is in progress to search for fluctuations in the zodiaal light of the order of a few percent, which could be attributed to spatial condensations of interplanetary dust or to solar activity.

The increase in sky brightness towards perihelion is due to increased zodiacal light brightness. The quantitative increase in zodiacal light brightness alone is shown in Figure 3 for specific viewing directions. Again, there is a difference between the inbound (upper) and outbound parts of an

Fig. 1: Observed sky brightness (zodiacal light plus star light) as a function of heliocentric distance R of Helios. The average brightness over the band at ecliptic latitude 16° is shown, normalized to the value at aphelion. The difference between the inbound (points) and outbound parts of the orbit is due to the tilt of the plane of symmetry. The peak at 0.8 AU is due to the passage of comet West.



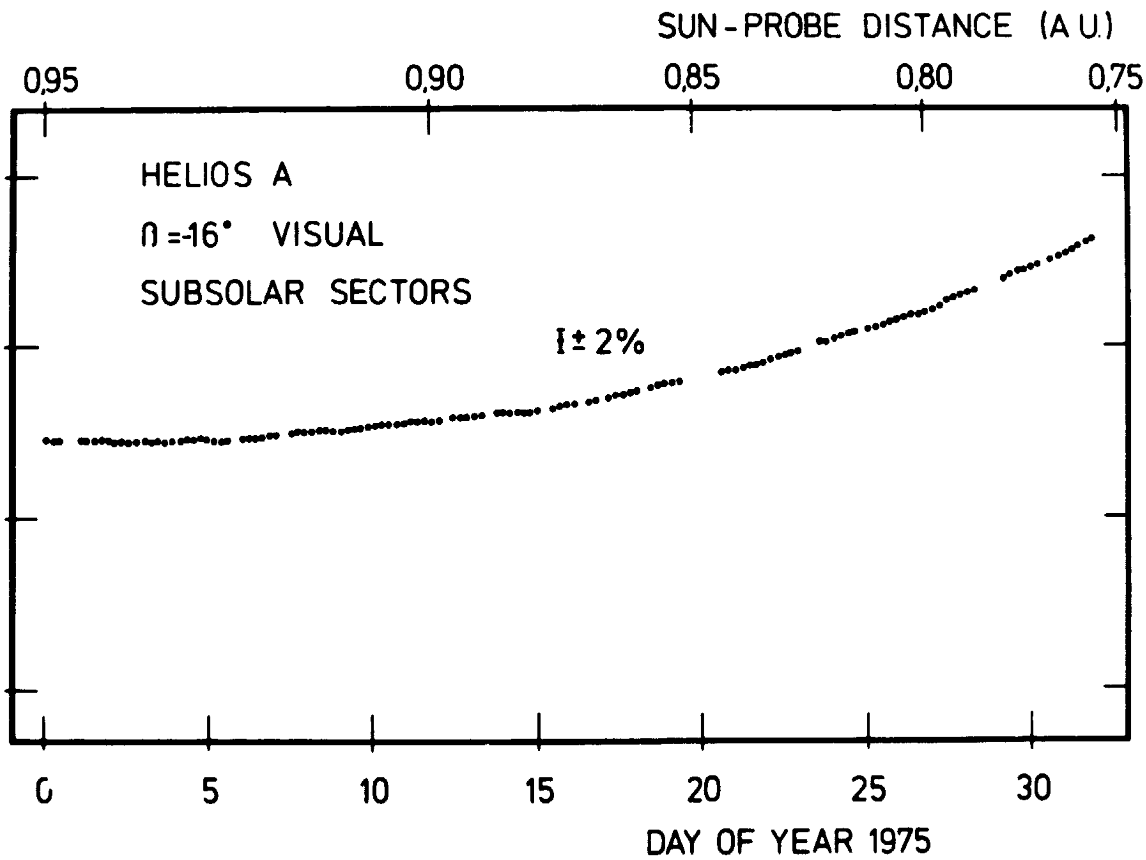
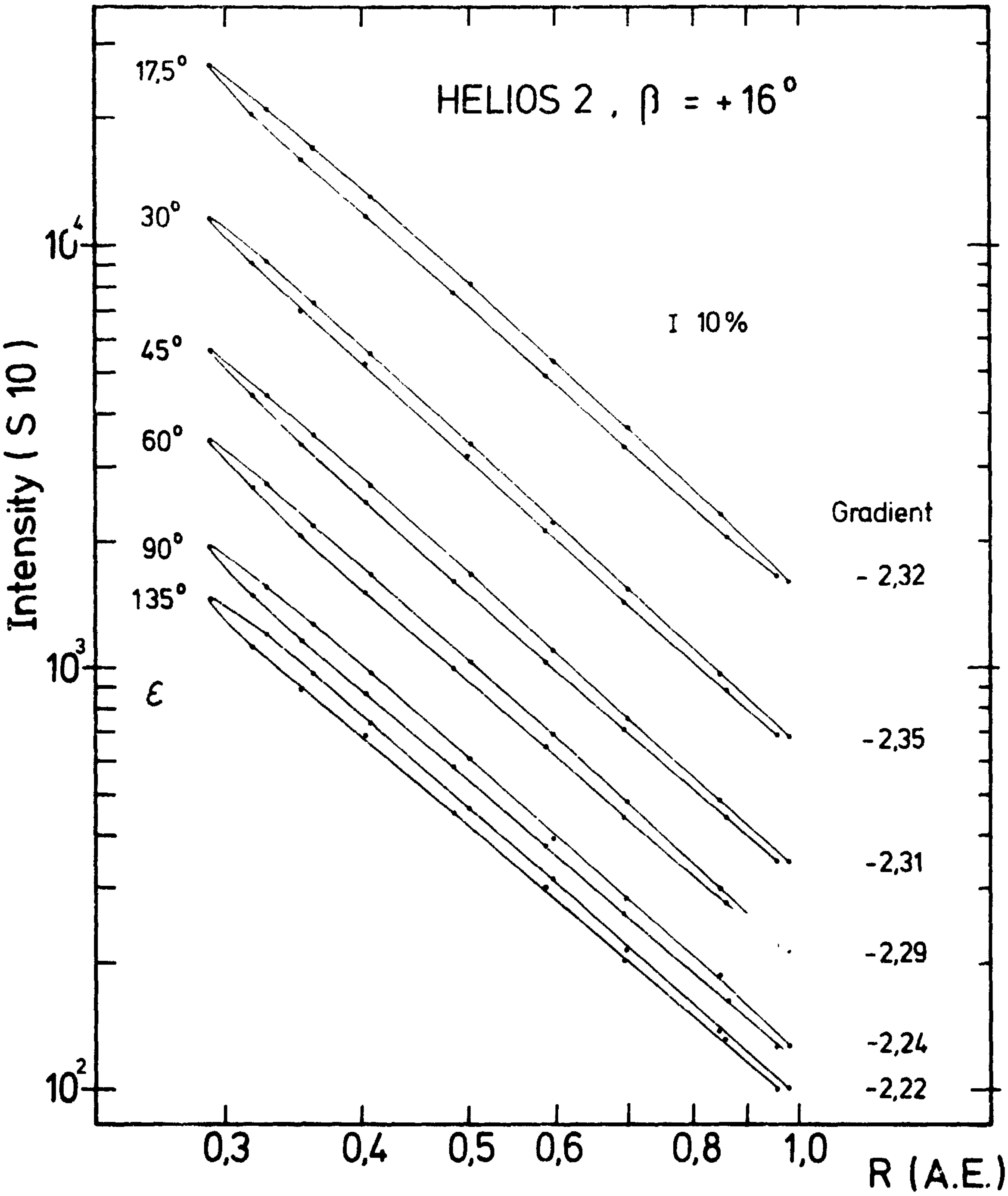


Fig. 2: Variation of sky brightness during January 1975. The intensity scale is linear in arbitrary units with suppressed zero.



<u>**Fig. 3**</u>: Variation of zodiacal light brightness with heliocentric distance R of Helios for various angular distances ε from the sun. 1 S10 is equivalent to 1.3×10^{-9} erg cm^{-2} s^{-1} sr^{-1} A^{-1}. Upper points refer to the inbound part of the orbit.

orbit, due to the tilt of the plane of symmetry. The measurements are well represented by straight lines, corresponding to a power law $I(R) \sim R^{-2.3 \pm 0.1}$ for all viewing directions. From this, the radial distribution of interplanetary dust can be determined as $n(r) \sim r^{-1.3 \pm 0.1}$, where r is the heliocentric distance of the dust particles. Detailed discussions (3,5,6) have shown that this power law-dependence should hold from less than 0.1 AU to outside 1 AU.

The spin axis of Helios is oriented towards the ecliptic pole and the photometers are scanning along bands parallel to the ecliptic. The tilt of the plane of symmetry of interplanetary dust with respect to the ecliptic, therefore, in general leads to a brightness difference between observations performed--for a given position of Helios on its orbit--at the same angular distance right or left of the Sun. This right-left asymmetry is largest when Helios is close to the nodal line of the plane of symmetry (uppermost set of observations in Figure 4). It should be zero when Helios is perpendicular

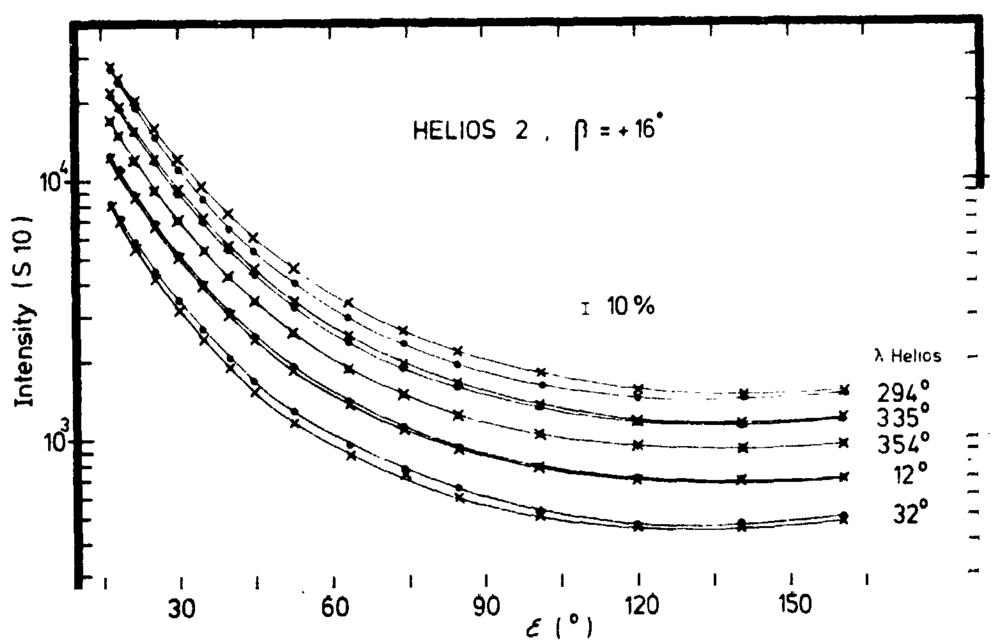


Fig. 4: Determination of the node of the plane of symmetry of interplanetary dust by the disappearance of the right-left asymmetry. Points refer to observations right, crosses to observations left, of the Sun. For each set of observations, the heliocentric longitude of Helios is given.

to the nodal line. The data presented in Figure 4 show exactly this predicted behavior: The right-left-assymmetry decreases while Helios is approaching the position perpendicular to the nodal line, vanishes at this point, then builds up again with opposite sign. It is the significance of these measurements that the longitude of the nodal line may be determined, free from models, directly from the longitude of Helios at which the zero crossing occurs. Figure 5 shows that the longitude of zero crossing may be determined within a few degrees from the variation of the right-left asummetry. The ascending node of the plane of symmetry of interplanetary dust was found from eight such independent determinations with Helios-1 and-2 as $\Omega = 87 \pm 4^0$. Similarly, the inclination of the plane of symmetry can be determined by an attitude maneuver. When Helios is at the nodal line, the tilt of the spin axis necessary to make the right-left asymmetry disappear is just equal to the tilt of the plane of symmetry. Such a maneuver was performed (Figure 6) and gave an inclination of the plane of symmetry of $i = 3.0 \pm 0.3^0$. There appears to be one well-defined plane of symmetry from inside 0.3 AU to at least 1 AU (10). The plane found by Helios clearly deviates from Jupiter's orbital plane or the invariable plane of solar system ($\Omega = 107^o$, $i = 1.6^o$). This deviation still has to be explained. electromagnetic forces associated with the moving interplanetary plasma are possible candidates for such an explanation.

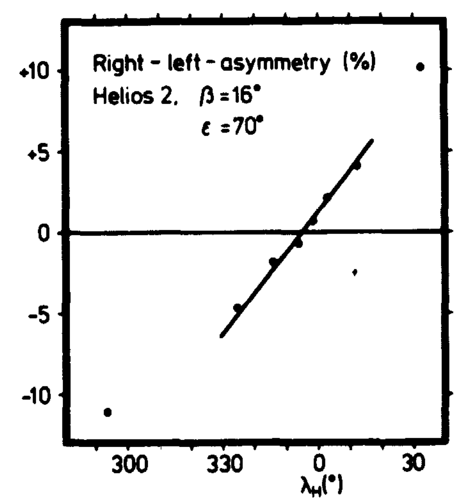


Fig. 5: Determination of the longitude of Helios at which the right-left assemetry dissappears. The points give the average asymmetry observed for angular distances $\leq 70^o$ from the Sun.

Future work will include a search for a change in particle properties with heliocentric distance, which should show as a change in color and polarization of the zodiacal light. An extension of the Milky Way photometry (7) and evaluation of the comet observations are also desirable. Because Helios is situated far from any disturbing sources related with the Earth's atmosphere, it is especially well suited to search for short-time fluctuations

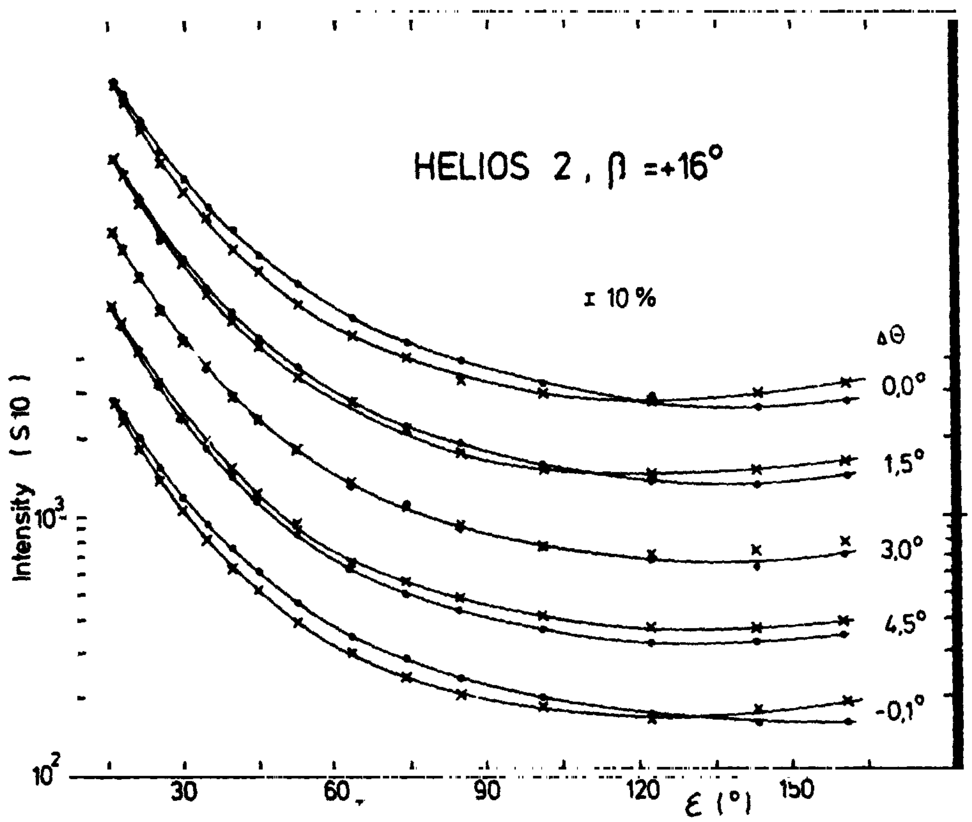


Fig. 6: Determination of the inclination of the plane of symmetry by an attitude maneuver on Days 341/342, 1977, close to the ascending node of the plane of symmetry. The intensity scale is valid for the lowest curve only, others are displaced by a factor of 2. Points refer to observations right of the Sun. θ gives the tilt of the spin axis from its nominal position (towards the ecliptic pole).

with solar activity or long-term variations with solar cycle. Any observable effects would be important clues for the clarification of the dynamics of the dust particles. It is for these topics that continued observation through the plane of maximum solar activity are extremely valuable.

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THE MICROMETEOROID ANALYZER (E 10)

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MICROMETEOROID EXPERIMENT - DATA ANALYSIS

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The objective of the micrometeoroid experiments on the Helios mission is to investigate the distribution of interplanetary dust in the inner solar system, to study its dynamics and to determine the physical and chemical characteristics of micrometeoroids. Each spacecraft carries on board two sensors: the ecliptic sensor measures dust particles which have trajectories within or close to the ecliptic plane while the south sensor (Helios-1) and the north sensor (Helios-2) detect particles with highly inclined trajectories. The ecliptic sensor is shielded by a thin film as protection against solar radiation. Micrometeoroids are detected by the electrons and ions produced upon impact onto the sensor and the ions are mass analysed in a time-of-flight spectrometer. From the charge released and from the rise-time of the charge pulse, the mass and speed of micrometeoroids are derived. Orbital information of interplanetary dust particles is obtained from the radial and azimuthal distribution of the impacts. The chemical composition of micrometeoroids is characterized by the impact mass-spectra from individual particles.

About 25 impacts have been recorded per revolution of a Helios spacecraft around the Sun. Figure 1 shows the orbits of the Earth and Helios-1. Superimposed on the Helios orbit are the positions where impacts were observed. The bars attached to the heavy dots represent the sensor pointing direction at the time of impact. The length of the bar indicates the measured pulse height of the positive impact charge, which roughtly correspond to the particle's mass.

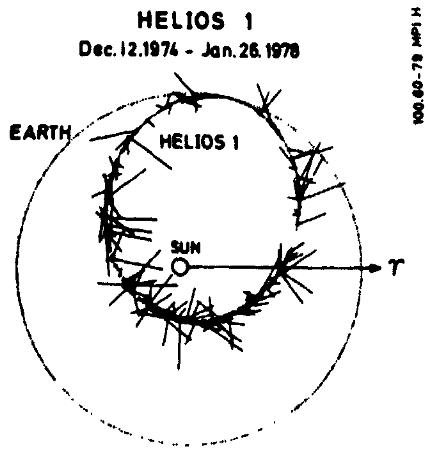

Fig. 1: Impacts detected during the first 6 orbits of Helios-1 around the Sun. Bars attached to the heavy dots indicate the pointing direction of the experiment at the time of impact. The length of the bars represent the magnitude of the charge released upon impact.

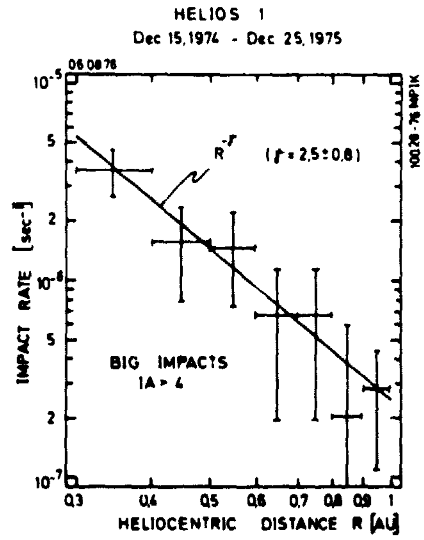

Fig. 2. Radial variation of the observed impact rate onto the micrometeoroid experiment.

The highest impact rate of approximately 0.5 impacts/day of particles with masses $m > 10^{-12}$g observed was observed as perihelion (0.3 AU). Figure 2 shows the radial dependence of the impact rate. The increase of impacts towards the Sun can be fitted by a power law with an exponent of -2.5 ± 0.8.This measurement is compatible with both measurements of the dust impact rate at 1 AU (1) and the increase of the zodiacal light intensity towards the Sun (2).

Each micrometeoroid impact is identified by the measurement of a time-of-flight mass spectrum of the positive ions released upon impact. Figure 3 gives the raw spectrum of an individual impact and the best fit of the ion mass spectrum. Mass analyses of the spectra showed that 40% of the observed spectra have the peak abundance below 35 amu which corresponds to chondritic compositon; likewise, 40% have peak abundances above 35 amu which are preliminarily identified as Iron meteroids (3). Twenty percent of the spectra could not be identified in either class.

The azimuthal distributions of impacts which were observed inside 0.55 AU from the Sun on both the ecliptic and the south sensors are displayed in Figure 4. Each impact is represented by an area which corresponds roughly to the angular sensitivity with respect to azimuth. For each sensor three curves are shown: small particles (I A $\leq$ 2), big particles (I A > 2) and the sum of both. Most impacts on the ecliptic sensor were observed when it was pointing in the direction of motion of Helios (apex direction: 0^{o}). In contrast to that the south sensor detected most impacts when it was facing in between the solar (90^{o}) and antapex (180^{o}) directions. Orbit analysis showed that the "apex" particles which are predominantly detected by the ecliptic sensor have eccentricities e < 0.4 and semimajor axes a < 0.5 AU From comparison with corresponding data from the south sensor it is concluded that the average inclination of these particles is below 30^{o}. The excess of impacts on the south sensor have orbit eccentricities e > 0.4 and semimajor axes a > 0.5 AU β-meteoroids (4), which leave the solar system on hyperbolic orbits, are directly identified by the imbalance of outgoing (away from the Sun) and ingoing small particles. The data from the ecliptic and north sensors of Helios-2 are in agreement with the data from Helios-1 which indicates no strong north-south asymmetry of the interplanetary dust cloud.

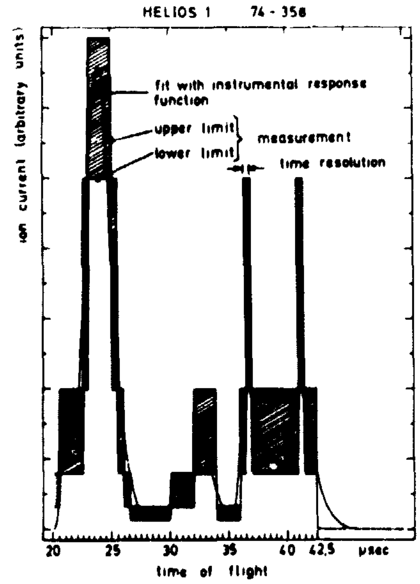

Fig. 3. Time-of-flight spectrum of the ions released upon impact of a micrometeroid onto a Helios sensor.

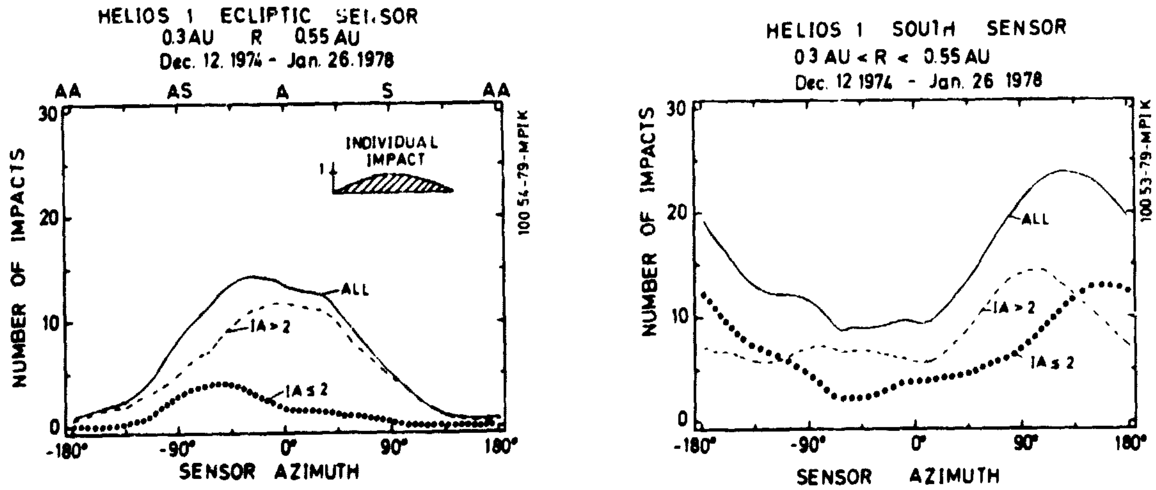

Fig. 4: Azimuthal distribution of impacts onto the ecliptic and south sensor. An individual impact is represented by the angular probability distribution (upper right hand corner) centered on the sensor pointing direction (apex direction = 0°, sun direction = 90°).
(a) ecliptic sensor
(b) south sensor

During the first 6 orbits of Helios-1 around the Sun, the experiment registered a total of 168 meteoroids; 52 particles were detected by the ecliptic sensor and 116 particles by the south sensor. Figure 5 shows the pulse-height distributions of the positive impact charge. The excess of impacts on the south sensor with respect to the impacts on the ecliptic sensor consist predominantly of small impacts (small pulse-height numbers). But large impacts, as well, were statistically significantly more abundant on the south sensor than on the ecliptic sensor. Zodiacal light observations show that interplanetary dust is concentrated towards the elciptic plane (5), and, hence, the ecliptic sensor should observe at least as many impacts as the south sensor. Therefore, it is assumed that the observed difference of the number of impacts is due to the only difference between the sensors, i.e. the entrance film in front of the ecliptic sensor. Extended laboratory studies of penetration effects succeeded in indentifying the penetration limit of the Helios film (6) for low-density projectiles. It was shown that only very low density particles (densities below 1 g/cm^3) produce upon impact the charge as observed by the south sensor but are not able to penetrate the film in front of the elciptic sensor. It was concluded that at least 20% of the particles detected by the south sensor have densities below 1 g/cm^3. This is in good agreement with the interpretation of zodiacal light observations which require fluffy particles as major parts of the interplanetary dust population (7).

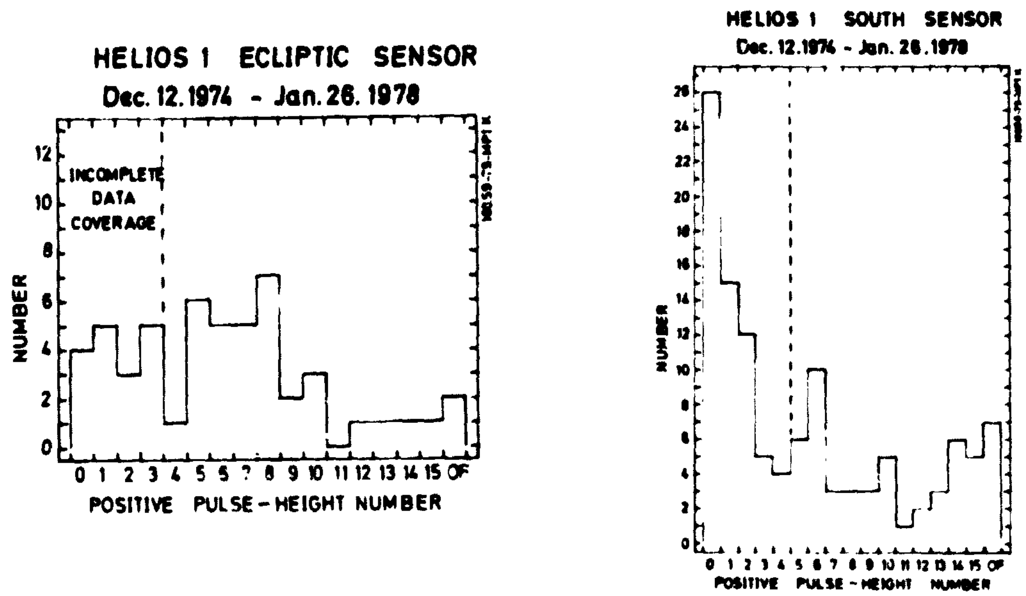

Fig. 5: Pulse-height distributions of the positive ion charge. The linear pulse-height number scale corresponds to a logarithmic charge scale covering 4 orders of magnitude of charge.
(a) ecliptic sensor
(b) south sensor

Osculating orbital elements of micrometeoroids have been computed from the impact speed, the spacecraft position and viewing direction at the time of impact. Due to the large field of view and the uncertainty of impact speed measurement, only probability distributions of the orbital elements of micrometeoroids are computed (8,9). Since particles in the observed mass range are subjected to radiation pressure, a mass-dependent model of radiation pressure (10) is taken into account. Many of the particles with masses below 10^{-11}g are hyperbolic orbits, whereas all particles above 10^{-11}g are on bound orbits. These larger particles contribute to the zodiacal light. The group of hyperbolic particles is classified in particles entering and leaving the solar system or being detected close to their perihelion. Table 1 shows that classification for the particles from the first 6 orbits of Helios-1 around the Sun.

Table 1: NUMBERS OF HYPERBOLIC PARTICLES
(assuming a mass dependence of the radiation pressure according to [10]).

	South Sensor	Ecliptic Sensor
Into the solar system	17	9
Out of the solar system	26	11
Detected close to perihelion	16	4

A large number of particles on hyperbolic orbits have been detected before perihelion on their inbound trajectory. These particles have their origin outside the orbit of Helios. The difference between the inbound and outbound particles are β-meteoroids, which are generated inside the orbit of Helios. Theoretical considerations yield that the melting of particles near the sun and the subsequent increase is radiation pressure which blows the particles out of the solar system is not an efficient source of β-meteoroids (11).

It has been shown theoretically (12,13) that there exists a strong coupling of small interplanetary and interstellar dust particles to the interplanetary magnetic field and plasma. A continuation of the Helios mission during times of increased solar activity may allow the experimental verification of these effects.

Acknowledgement:

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CELESTIAL MECHANICS (E 11)

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Short Description

The purpose of the experiment is a precise evaluation of the spacecraft orbit based on radio signal return times (=range) and frequency shift (=Doppler) measurements, at an accuracy of kilometers or less in the orbit plane. For known non-gravitational forces such as the solar radiation pressure, solar wind pressure, (smaller) radiation reactions, and for known signal path distortions by the solar wind plasma, the orbit in space and time can be used to test theories of gravity.

Achievements

Both missions, 1 and 2, were badly degraded (for E 11) by insufficient coverage (effective 0.5 year rather than 2 years) and quality of range measurements. Nevertheless, this mission is so far the best spacecraft mission for a test of theories of gravity because of the high orbital eccentricity, and semi-major axis and well-defined non-gravitational accelerations.

The latter are much easier to assess for Helios than for other missions, for the following two reasons: (1) its high spin rate reduces thermal gradients and tangential forces; (2) by accident the inclination angle of its solar arrays has such a value that surface normals point on average at some 45° with regard to the Sun that the solar radiation pressure does not depend sensitively on the time-varying surface absorptivity (a perpendicular reflection screen experiences twice the force of an absorbing screen). The reduction is by a factor of 30. In this way, radiation pressure can be determined with a relative accuracy of some $3 \cdot 10^{-3}$, just below the level of orbit deformations due to deviations from Newtonian behaviour. For earlier missions, non-gravitational forces were 10 to 30 times less well known.

A determination of post-Newtonian effects on the spacecraft orbit requires sophisticated software. In view of the large unknown non-gravitational perturbations, a simple Gaussian fit of just the searched-for post-Newtonian parameters is bound to give largely overoptimistic results; evidence of this is abundant. We, therefore, developed an iterated (extended batch) filter algorithm suitable to tackle any multi-parameter orbit determination. This filter, called COSMOS, has been written and tested by Dr. Eckhard Krotscheck at Hamburg, supported by Dipl.-Math. O. Bohringer, and is presently being applied to the real data.

Here is how COSMOS proceeds: Given at a particular time, a set of initial data and estimated values for a certain number of parameters describing perturbations, together with estimated uncertainties, COSMOS predicts their propagation in time; i.e. the program calculates a tube of growing cross section containing the predicted orbit. At the time of the next measurement, improved phase space and parameter space data are calculated, together with reduced uncertainties, and the next step begins. The uncertainty tube thereby acquires a shape similar to the legs of an insect, and (hopefully) converges towards the real orbit. Should there be an error in the physical model, or systematic errors in the measured data, the filter diverges. A divergent run is, therefore, the rule rather than the exception.

Krotscheck and Bohringer have tested our program on an orbit simulated at the institute of our co-experimentors. After several months they recovered it completely. In this process they discovered that the claimed value of the astronomical unit was in error by some 30 Km, that the conversion from universal time to ephemeris time had been performed with insufficient precision, and that the tropospheric corrections had not been included.

We are presently trying the program on real data. In this process we find ourselves repeatedly hampered by the fact that successive batches of range data, while intrinsically smooth at the $\lesssim$ 10 m level, are offset by kilometers or more in an erratic fashion. Cleaning the data appears to be a highly non-trivial procedure.

<u>Publications</u>

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FARADAY ROTATION EXPERIMENT (E 12)

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Experiment Purpose/Instrumentation

The scientific goal of this experiment is the investigation of the dynamic and quiescent structure of the magnetic fields and electron density in the solar corona. The analysis uses Faraday rotation (polarization) data from the linearly polarized S-band downlink carrier signal, which probes the solar corona during times of spacecraft superior conjunction.

Highlights of the Investigation--Helios E 12

A. Experiment Description

The short-period heliocentric orbit of the Helios spacecraft allows many repeated opportunities for conducting radio science investigations of the solar corona during superior conjunction. Since the orientation of the linearly polarized carrier signal is known as it leaves Helios, measurements of the coronal contribution to signal Faraday rotation Ω can be taken by tracking the received signal polarization and transforming this value back to the ecliptic. This Faraday rotation is related to the coronal magnetic field $\vec{B}$ and electron density N_e by

$$\Omega = \frac{C}{f^2} \int N_e \vec{B} \cdot d\vec{s} \qquad \text{radians} \tag{1}$$

where $C = 2.36 \times 10^4$ in mks units

$f = 2.296$ GHz

and the integral (1) is taken along the (straight line) ray path.

The data for the Faraday rotation experiment consists of $\Omega(t)$ taken typically at 10 second intervals. Using the known occultation geometry, one may obtain $\Omega(r,\theta,\phi)$, where (r,θ,ϕ) are the heliocentric coordinates of the point of closest approach of the ray path (the "solar offset"). At S-band, one generally obtains good coronal Faraday rotation data on Helios at solar offsets R between

$$2\ R_S < R < 12\ R_S . \tag{2}$$

Table 1 is a list of the Helios occultation opportunities, i.e. periods for which (2) is fulfilled, in the years 1975 - 1980. The number of polarization tracking passes and average length of pass at each occultation are also noted. A dash entry indicates that the tracking station was not available for a given occultation interval because of deficiencies in instrumentation. A zero entry means that the station could have been used for the Faraday rotation experiment, but the tracking station was needed for other projects. Helios operations

Table 1 - Helios Solar Occultations

Year	Interval	Total Days	Helios s/c	Solar Limb	Tracking Passes/Average Length of Track (hrs) DSS 14	DSS 43	DSS 63	Effelsberg	Total
1975	14 Apr - 01 May	18	1	W	9/6.3	-	-	5/7.8	14/6.8
1975	12 May - 09 Jun	29	1	W	2/5.1	-	-	10/4.2	12/4.4
1975	24 Aug - 30 Aug	7	1	W	2/6.0	-	-	6/6.9	8/6.7
1975	01 Sep - 05 Sep	5	1	E	4/4.9	-	-	4/7.4	8/6.2
1976	08 May - 14 May	7	2	W	3/4.4	-	-	7/7.5	10/6.6
1976	19 May - 06 Jul	49	2	E	3/4.7	-	-	23/8.1	26/7.7
1976	16 Jul - 05 Aug	20	2	W	0	-	-	11/8.7	11/8.7
1976	15 Sep - 24 Sep	10	2	W	0	-	-	-	0
1976	18 Sep - 21 Sep	4	1	W	0	-	-	-	0
1976	22 Sep - 25 Sep	4	1	E	0	-	-	-	0
1976	26 Sep - 03 Oct	8	2	E	0	-	-	-	0
1977	20 May - 02 Jun	14	2	W	-	7/0.9	7/2.6	-	14/1.8
1977	26 Jun - 19 Jul	24	2	W	7/3.7	14/1.7	16/3.8	-	37/3.0
1977	30 Sep - 05 Oct	6	2	W	2/8.6	0	4/2.5	-	6/4.5
1977	08 Oct - 11 Oct	4	2	E	3/4.9	0	2/2.5	-	5/3.9
1977	08 Oct - 10 Oct	3	1	W	1/1.0	0	1/2.0	-	2/1.5
1977	12 Oct - 14 Oct	3	1	E	1/4.7	1/1.3	2/1.6	-	4/2.3
1978	08 Jun - 29 Jun	22	2	W	2/1.9	0	0	-	2/1.9
1978	11 Oct - 15 Oct	5	2	W	1/1.9	0	0	-	1/1.9
1978	17 Oct - 20 Oct	4	2	E	1/1.4	0	0	-	1/1.4
1978	27 Oct - 29 Oct	3	1	W	0	0	0	-	0
1978	30 Oct - 01 Nov	3	1	E	0	0	0	-	0
1979	21 Oct - 25 Oct	5	2	W				-	
1979	26 Oct - 29 Oct	4	2	E				-	
1979	14 Nov - 16 Nov	3	1	W				-	
1979	17 Nov - 19 Nov	3	1	E				-	
1980	30 Oct - 02 Nov	4	2	W				-	
1980	03 Nov - 06 Nov	4	2	E				-	
1980	02 Dec - 03 Dec	2	1	W				-	
1980	04 Dec - 06 Dec	3	1	E				-	
Total		280			41/4.8	22/1.4	32/4.5	66/7.4	161/5.1

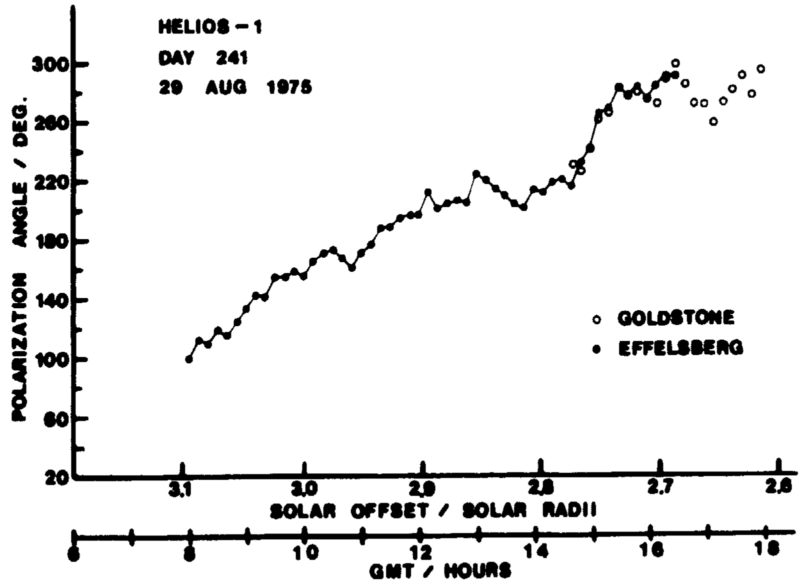


Figure 1. Coronal Faraday rotation of Helios carrier signal during tracking pass at Effelsberg on 29 Aug 1975.

at Effelsberg were terminated in August 1976. Due to technical difficulties, the Faraday rotati..n experiment could not be continued at the German replacement station in Weilheim. The NASA Deep Space Network added automatic polarization tracking at the 64m stations in Canberra (DSS 43) and Madrid (DSS 63) in early 1977. Goldstone (DSS 14) was refurbished in May 1977 and was thus unavailable for the first occultation of Helios 2 in that year. The DSN was committed tc full coverage of the Viking primary mission in September 1976. This unfortunately left no time for observations of the unique "double occultation" of both Helios spacecraft.

Additional details concerning the experimental technique and instrumentation may be found in (2). The problem of correction for the Earth's ionosphere is addressed in a supplementary work (6).

B. Areas of Investigation

Three significantly different variations in the coronal Faraday rotation may be observed during occultation:

(1) a slowly varying rise or fall in measured Faraday rotation which is obviously due to the increasing or decreasing ray path offset in a slowly-rotating quasi-static corona.

(2) a ubiquitous random oscillation in $\Omega(t)$ with higher fluctuation amplitude at lower solar offset distances.

(3) an occasional almost discontinuous drop or jump in the polarization angle which may be due to transient phenomena in the corona.

Each of the above aspects of the Faraday rotation data has been analyzed and some highlights of these investigations are presented here.

(1) Quiescent corona and large-scale sector structure

The measured coronal Faraday rotation during an entire Effelsberg tracking pass on 29 Aug 1975 is shown in Fig. 1. A large positive value of Ω was registered at this time at solar offsets from 2.6 - 3.1 R_S. The two hours of station overlap with Goldstone demonstrate that the measured polarization angle and even the superimposed fluctuations are seen at both widely-separated ground stations.

The observations from the first occultation of Helios 1 in April 1975 are presented in Fig. 2. The rotation of the quasi-static corona is responsible for the zeros in recorded Faraday rotation on days 110 and 115. The coronal magnetic field configuration at these points causes the signal to undergo negative and positive Faraday rotations along different path segments, which exactly cancel out upon traversal of the entire corona. When $\Omega(t)$ is changing rapidly, it is necessary to maintain continuous polarization tracking in order to distinguish between Ω and $\Omega \pm n\pi$. The problem that can arise is illustrated by the sets of points labeled "180° ambiguity" in Fig. 1, when only the Goldstone station was operating.

Under the assumption that the corona not change its distribution of magnetic field $\vec{B}$ and electron density N_e during an occultation, one may derive the rough longitudinal variation of $N_e\vec{B}$ which is consistent with observed magnetic field polarities in interplanetary space (3). An example of such a derived longitudinal configuration is given in Fig. 3. The diagram represents the Sun, viewed from the North ecliptic pole at 26.0 Apr 1975, cut into six longitudinal bins containing differing values of $N_e\vec{B}$. The arrows in each bin indicate the polarity of the derived magnetic field (assumed radial). The arrows in the outer circle are the daily IMF polarities as inferred from polar cap magnetograms (Svalgaard-Mansurov Effect). The computed coronal Faraday

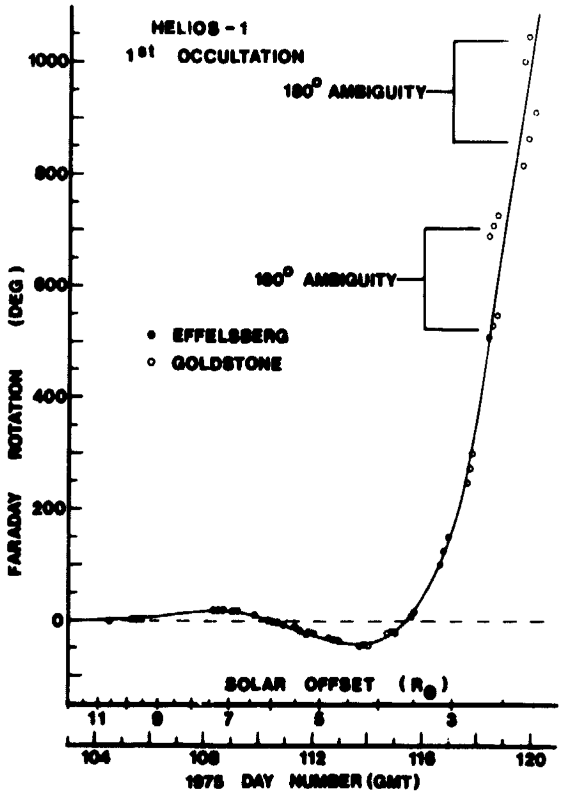


Figure 2. Coronal Faraday rotation during inbound occultation of Helios 1 on solar west limb in April 1975. The circles are observations; the solid curve is the theoretical result from the model of Fig. 3 (3).

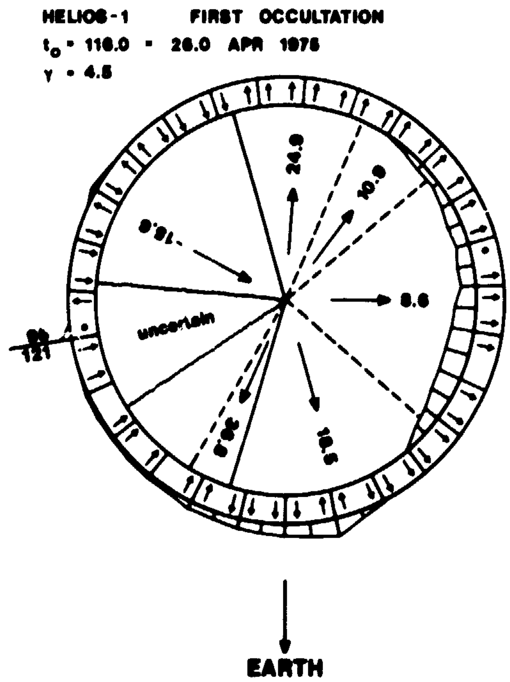


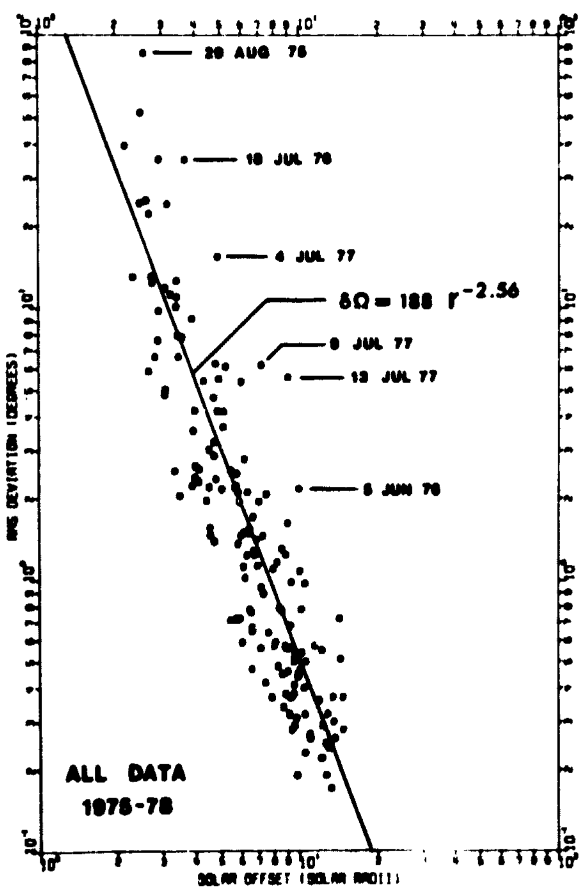
Figure 3. Large-scale coronal structure derived from Faraday rotation measurements during first occultation of Helios 1 in April 1975. View is from solar north pole onto the ecliptic. Heliolongitude is divided into 6 bins of differing NB. Other details are given in the text and in (3).

rotation from this configuration is given by the solid curve in Fig. 2. Using less than six bins in longitude, one cannot determine a configuration which gives a satisfactory agreement with the observed Faraday rotation. Models with more than 6 bins were not tested since the integrated Faraday rotation data are simply inadequate for determination of smaller-scale features.

The structure derived in Fig. 3 agrees with the white light coronagraph data taken at the west solar limb at 1.5 R_S. Intensity enhancements and depletions in the coronagraph data are indicated in the areas stretching outside the outer circle and inside the inner circle of Fig. 3. The coronal hole seen in white light on the solar west limb on 26 Apr 1975 is matched in longitude by the derived minimum in N_eB. Similar success in comparison with observed solar longitudinal structure was reported in (5), where solar radio maps at 2.8 and 11 cm were taken on the Effelsberg telescope in support of the May 1976 occultation of Helios 2.

(2) <u>Faraday rotation fluctuations</u>

The slowly-varying component of the function $\Omega(t)$ is superimposed with finer scale fluctuations, which increase in intensity at smaller solar distances (Fig. 4). Preliminary spectral analyses of representative data segments have indicated the presence of peaks in the power spectrum at certain preferred frequencies (7,8). Since these fluctuations were also observed in group delay time data taken simultaneously, it was conjectured that MHD waves in the fast mode were present in the outer corona. Another possibility is that the density oscillations are caused by non-linear propagation of the intermediate (Alfvèn) wave. The Faraday rotation observations on Helios appear to offer one of the few methods available for direct detection of Alfvènic disturbances in the region of high solar wind acceleration.



<u>Figure 4</u>. Amplitude of Faraday rotation fluctuations as a function of solar elongation. The root-mean-square deviation of Ω from its linear large-scale trend during each pass falls off sharply with solar distance (8).

(3) Faraday rotation transients

On a number of occasions during Helios tracking at superior conjunction, the measured polarization angle has abruptly moved to a new value tens of degrees from the projected baseline. The best example of this behavior was recorded on 18 July 1976 during a long tracking pass at the Effelsberg ground station (lower panel of Fig. 5). The magnitude, duration and signature of this event were similar to those seen during the solar occultation of Pioneer 6 during solar maximum (1). A simple model of the possible magnetic and plasma density structure of the coronal disturbance causing this Faraday rotation transient has been proposed by Bird et al. (4). The occurrence frequency of such events was determined to be of the same order as that of coronal mass ejection events, which were observed by orbiting coronagraphs on OSO-7 and Skylab.

The Faraday rotation observations of spacecraft signals passing through a coronal transient offer the possibility of directly determining the magnetic field configuration within the disturbance. The separation of magnetic and electron density effects can be accomplished by comparing coronal images during and prior to appearance of the transient. Unfortunately, the

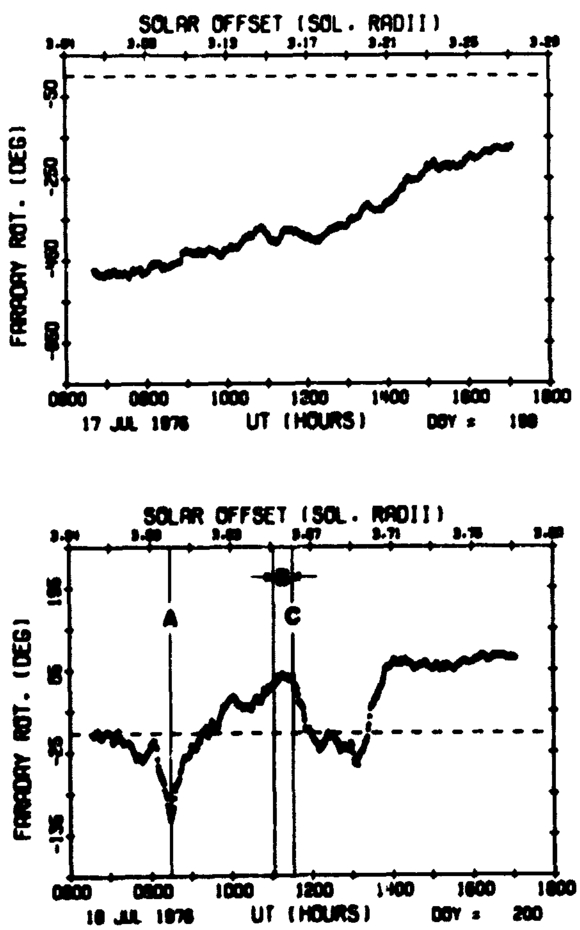


Figure 5. [illegible] rotation transie[illegible] on west solar limb on [illegible] 1976. The transient [illegible] (l[illegible] panel) may be compar[illegible] the quiet trace [illegible] previous day (upper p[illegible] which was taken at a s[illegible] solar offset (4).

equipment and conditions for making white light coronal images and Faraday rotation observations on spacecraft during solar occultation have never yet been achieved. The first such opportunity will occur in late 1979 during the annual occultations of the Helios spacecraft. A cooperative research effort will be conducted with the help of the coronagraph on the Solar Maximum Mission (SMM), which should be in operation at that time. A second measurement interval would occur in late 1980 should both SMM and Helios still be operational. The Helios E12 experimental team is participating in this cooperative investigation within the framework of the SMM Guest Investigator Program.

C. Extension to Natural Coronal Probe Signals

The success enjoyed with the Faraday rotation experiment on the Helios spacecraft has been extended to observations of linearly polarized pulsar signals during solar occultation. About 10% of the over 300 known pulsars are located close enough to the ecliptic plane to obtain a measureable coronal Faraday effect at their annual superior conjunction. The observations of PSR 2045-16 at the Effelsberg radio telescope in January 1978 (9) were somewhat inconclusive, since the recorded coronal contribution was only 3-4 times greater than the typical measurement error. Later observations of PSR 0525+21 (June 1978) showed a coronal Faraday rotation of $\Omega = -80^{\circ}$ at a minimum solar offset of about 4.8 R_S over the south solar pole (10). Pulsars, in contrast to continuous emitters, present no serious observational difficulties close to the Sun. The solar sidelobe interference at decimetric wavelengths is about 100 times stronger than the source, but the pulsed nature of the pulsar radiation allows integration of the signal over the pulse window without driving the telescope off source. Present plans call for a continuation of this experiment at Effelsberg in 1979 and 1980, during which the polar corona is expected to assume its typical solar maximum configuration.

D. Summary

The Faraday rotation experiment on the Helios mission has been shown capable of providing important information about the quiet and disturbed magnetic structure of the solar corona in the range 2 - 12 R_S. The unexpectedly long lifetime of the Helios spacecraft presents the possibility of continuing this investigation up into solar maximum, which would thereby complete one solar cycle over which Faraday rotation observations (together with Pioneers 6 and 9) were made. Dynamic effects such as coronal transients should be occurring at a much higher rate during solar maximum. This will increase the chances for obtaining simultaneous recording of an event in white light (coronagraph on SMM) and Faraday rotation (Helios in solar occultation) during the unique observation opportunities in late 1979 and 1980.

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HELIOS OCCULTATION EXPERIMENT—TIME DELAY MEASUREMENTS (E OC)

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The experiment used the S-band radio subsystem of the Helios spacecraft to measure the Doppler frequency, range and columnar electron content during solar occultations. These data were collected from launch date until October 1975 and June 1976, respectively, when terminated by a breakdown of the transponders aboard. For this experiment it was especially important to use the 210 ft. antennae of the NASA Deep Space Network. The objective of the experiment is to determine the spatial distribution and temporal variations of the solar plasma by remote sensing as close as about 3 solar radii, where the Sun is inaccessible to *in situ* measurements of electron density (1).

Highlights

There are several highlights from the scientific data analysis of the Helios occultation experiment. The most striking result obtained so far is that for the first time experimental evidence of hydromagnetic waves propagating outward from the inner solar corona into the interplanetary medium has been established (2,3,9,12). Generally, hydromagnetic waves are associated with oscillation of the solar and interplanetary magnetic field and of the plasma density, as well. These waves are thought to be important in the process of energy transport heating the solar chromosphere and corona. We observed such wave phenomena from an analysis of the temporal variations of the columnar electron content (number of electrons along the ray path) measured within heliocentric distances as close to the Sun as about 6 solar radii (Helios-2) up to 50 solar radii (Helios-1).

c.8

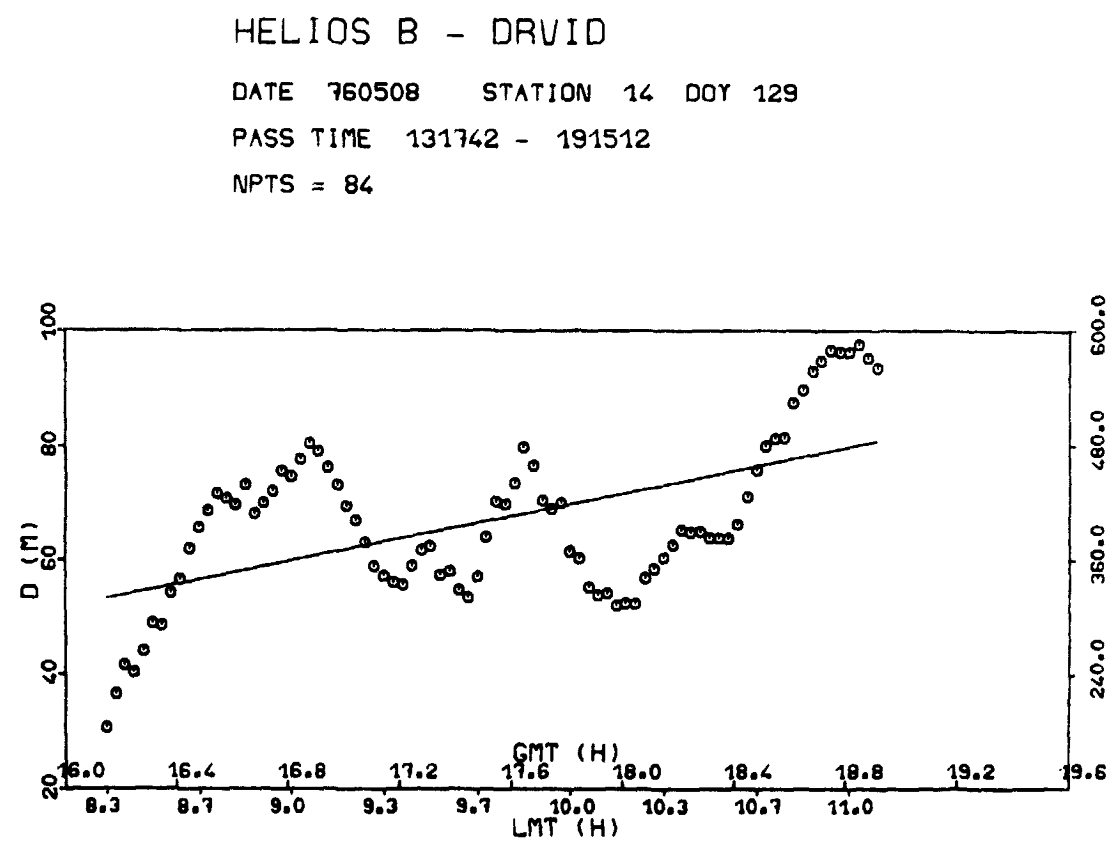

Fig. 1

Figure 1 shows a representative set of measurements collected on May 8, 1976 (entry phase of occultation, Helios 2; distance ray path, sun about 10 solar radii); relative changes of the electron content with order of magnitude 4×10^{20} electrons/m^2 are plotted vs. 3 hours of observation (6). The technique of measurement was developed at JPL in 1969; refined ranging equipment was operated for the first Helios solar occultation in 1976. The strength of the Helios ranging signal was extraordinarily high compared to similar interplanetary missions, so a fine structure is detectable in the time variations measured (4).

Figures 2 and 3 represent typical results of a spectral analysis showing the normalized power density of an electron content data set (May 8, 1976) and the corresponding electron densities, respectively (9,12). These spectra were derived by using a maximum entropy approach especially suitable for analyzing short and noisy data sets, as well. The fundamental frequency of the density oscillations associated with such hydromagnetic waves turns out typically to be 0.2×10^{-3} Hz, corresponding to a period of approximately 1.5 hours. Even higher harmonics can often be distinguished as stable spectral components during successive days (e.g. 0.5×10^{-3} Hz or about 30 minutes). Far away from the Sun the time periods tend to become smaller. More than 50% of the data measured show periodic structures. The spectral peaks of the electron density contain information on the wave amplitudes, thus enabling us to estimate the energy density involved and the energy flux density transported by such waves. The interpretation in terms of hydromagnetic waves in the solar atmosphere is strongly supported by a spectral and cross-correlation analysis

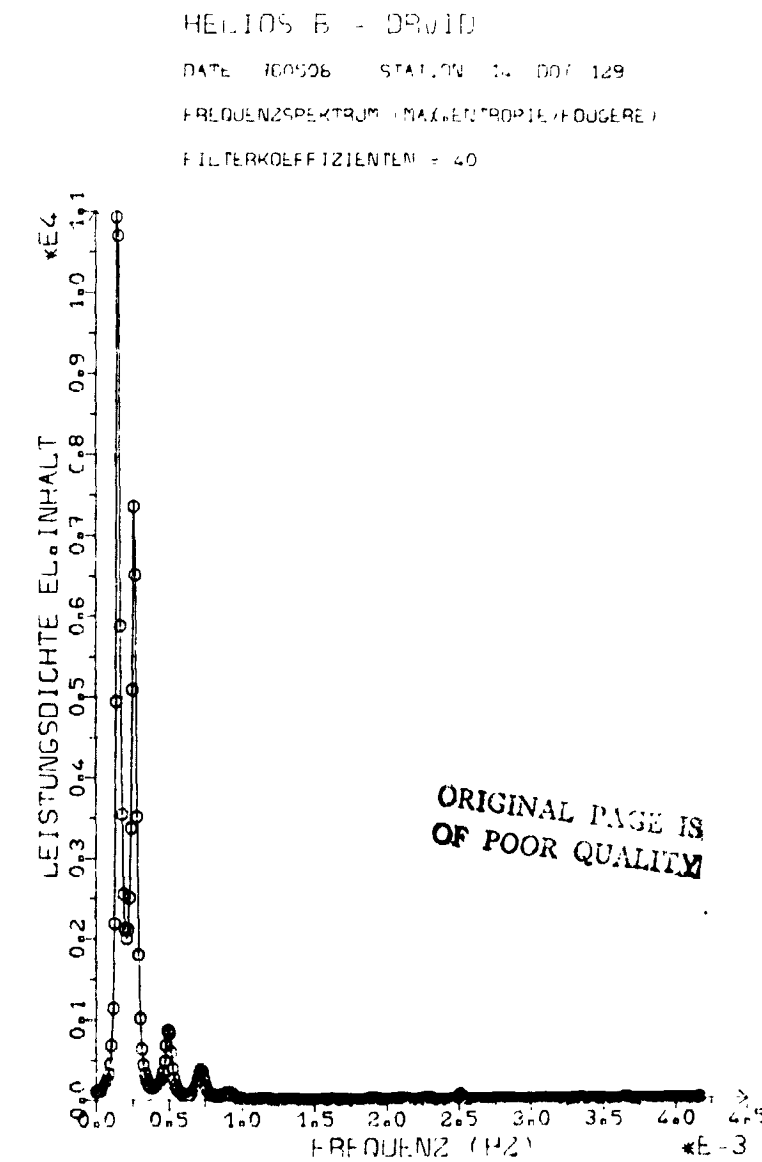

Fig. 2

of the Helios Faraday rotation measurements simultaneously collected along the same ray path at the same signal frequency (6,9). Generally, there is excellent agreement between the results from these two data streams measured via physical effects completely different from each other. Among comparable interplanetary space missions, the Helios mission allowed, for the first time, radio science to make such complementary measurements of wave propagation effects. The investigations covering this wave analysis are to be continued; several publications are being prepared.

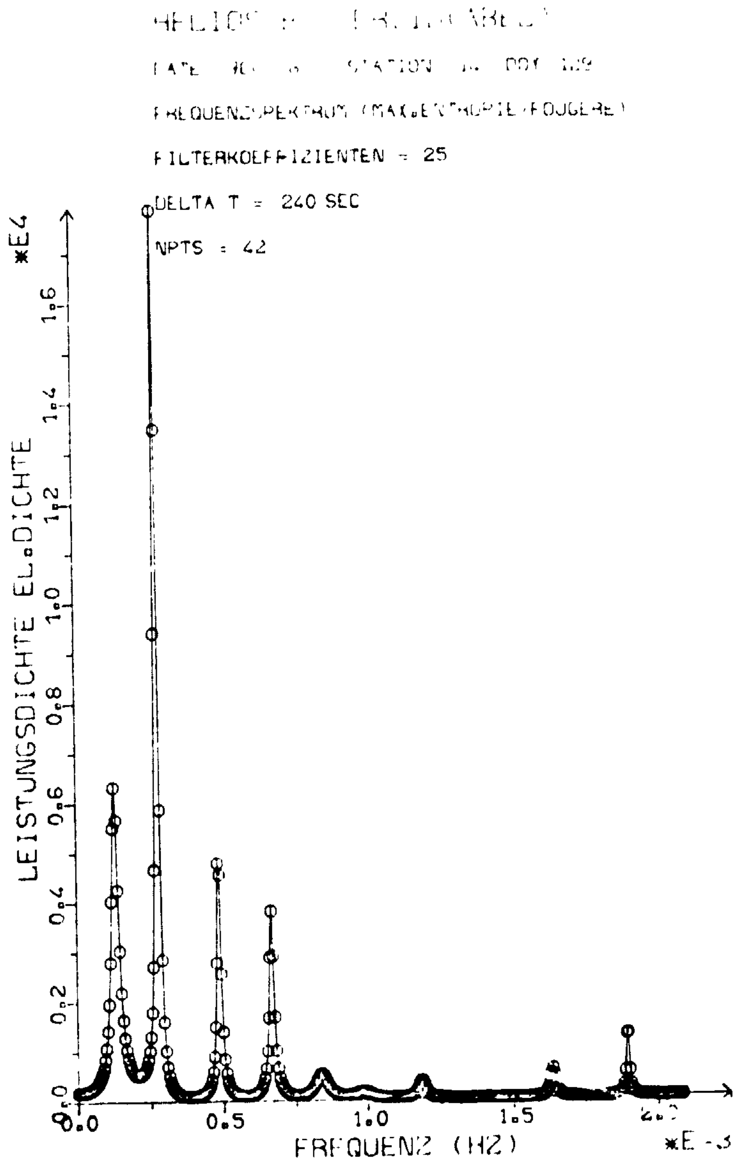

Fig. 3

As a new application of using radio tracking spacecraft data from solar occultations, a method has been developed, using the Helios occultation experiment, to determine the radial speed of propagating solar plasma disturbances from two-way, coherent Doppler data of a single ground station (10). The method exploits the spatial separation (typical value is 20×10^3 km) of the telemetry up- and downlink between station and spacecraft due to their different relative velocities with respect to the line of sight between Earth and probe. Solar plasma disturbances intersect the up- and downlink, giving rise to a peak in the autocorrelation function of the Doppler residuals as taken from a precise orbital determination. This method of analysis was first applied to Helios-2 data, generally revealing two peaks corresponding to a low and high propagation speed, respectively; e.g. varying from 200 to 400 km/s to 600 to 1000 km/s. Specifically, a Doppler data set collected on May 28, 1976 (exit phase, Helios-2; distance some 8 solar radii), yields approximate values of 240 and 950 km/s. It is possible that the temporal variability in the autocorrelation function taken from a tracking pass of usually several hours indicates a changing velocity from a predominant plasma stream, or a superpositioning of several plasma streams, which tends to smear the autocorrelation peaks. Further analysis is promising and continuing.

The inversion of the Helios electron content measurements turned out to be another highlight of our occultation experiment (1,7,11). The derivation of electron density values is most important to the description of solar plasma phenomena in terms of physical quantities such as energy density and power flux (e.g., Fig. 3). Following two alternative, complementary approaches, inversion methods have been set up for this experiment to get electron densities out of electron content for the first time in remote sensing of solar plasma: Either a gross, but numerically stable, structure is derived for the electron density distribution in space, or the spatial and temporal power of resolution is inceased by using an inversion procedure that takes into account statistical properties of the data measured and the densities to be deduced (11). The problem of choosing statistical weights was solved for remote sensing by taking a Kalman-type filter algorithm to compromise resolution vs. instability (7). It was possible by using this approach to deduce two-dimensional electron densities resolving a radial dependence as well as variations in solar longitude (closest heliocentric distance 5.8 solar radii). The plasma is allowed to show a steady-state model profile for electron density and velocity describing the overall fall-off in density and the solar wind properties. This _a priori_ information is used in our adaptive weighting scheme for inversion, improved by extrapolating information from two additional sources (4,8): Earth-bound observations of the scattered light of the Sun (coronagraph) and _in situ_ measurements of electron density along the Helios trajectory (heliocentric distance greater than 65 solar radii at perihelion). The inversion turned out to be stable, even if performed for each individual data point which yields a maximum resolution in time (sampling rate 2 minutes). Generally, the inversion procedure takes sequential averages from appropriately selected subsets of data.

Performing this Helios occultation experiment resulted in several opportunities to observe transient phenomena of extraordinary solar events. One exciting example is an electron content data set collected on April 30 and May 1, 1976 (two weeks after perihelion), by Helios-2. At a distance ray path of 26 solar radii to the Sun, the enormous variation in electron content was 6 times the steady-state background value within about 2.5 hours of observation. From Earth-based astronomical observations, this event could be identified as a large solar flare ejecting huge quantities of solar plasma across the Helios ray path into interplanetary space. Combining these different sources of information made possible the determination of flare propagation speed to be as high as approximately 900 km/s. Work is still in progress on the study of further transient events of enhanced solar activity as obvious from several sets of electron content measurements.

A major objective of the Helios occultation experiment was to determine characteristic quantities of an empirical model for the coronal electron density distribution (3,4). This part of our scientific data analysis is near completion (8); three model parameters were derived including their standard deviations. The model describes a spherically symmetric, steady-state electron density distribution covering heliocentric distances between approximately 3 and 215 solar radii (up to the Earth's orbit). A high-precision orbit determination program developed at JPL was taken to evaluate about 3.5 months of Helios-2 time delay data around solar occultation. Apart from their physical significance, such solar electron density models are especially useful for navigational purposes in space mission operations, as well. Improving these models means increased accuracy for correcting tracking data for solar plasma effects and allowing for a proper noise level. It could be verified for our experiment that the values derived for elecron density are consistent with what was measured by scattered light on Earth and <u>in situ</u> along the Helios trajectory (8).

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16. Abstract

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