J. Geophys. 42, 645–657, 1977

Journal of Geophysics

Interaction of Low-Energy (> 80 keV) Protons with the January 6 and 8, 1975, Shock Waves: Helios-1 Observations*

A.K. Richter and E. Keppler

Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau 3, Federal Republic of Germany

Abstract. During January 6–8, 1975, both the fluxgate magnetometer (IGM, Braunschweig) and the plasma experiment (MPE, Garching) on board HELIOS 1 observed two shock-events separating certain regions in space, which exhibit different structures as far as the type and the magnitude of interplanetary fluctuations are concerned. At the same time the low-energy charged particle spectrometer (MPAE, Lindau) on board HELIOS 1 measured the energy- and directional-distribution of 80–6150 keV protons in 16 different energy- channels and in 16 different directions for each energy simultaneously. The influence of the observed interplanetary fluctuations on the energy-, the spectral- and the directional distributions of these low-energy protons are discussed in view of local acceleration mechanisms and interplanetary propagation effects.

Key words: HELIOS mission – Interplanetary shock waves – Proton observation in interplanetary space.

Introduction

On December 10, 1974, the solar probe HELIOS 1 was launched into a heliocentric orbit with an aphelion of ~0.98 AU and a perihelion of ~0.3 AU, respectively. The spaceprobe is spinning at a rate of about 1 rev./s with its spin axis normal to the ecliptic plane. The charged particle spectrometer (CPS) of the Max-Planck-Institut für Aeronomie, Lindau, Germany, on board HELIOS 1 measures electrons and protons in the energy range 20 keV – 1 MeV and 80–6150 keV, resolved in 16 quasilogarithmically scaled energy-intervals and in 16 angular directions. The separation of the electrons and protons is performed by an inhomogeneous magnetic field of ~800 Gauss. The instrument's aperture is pointing radially outwards of the spaceprobe in the ecliptic plane with an

* Dedicated to Prof. G. Pfotzer on the occasion of his 68th birthday

opening angle of 10° half angle. At the highest bitrate energy-integral, angular distributions for electrons or protons are obtained every 13.5 s, while a full set of spectral measurements in all 16 directions takes 108 s (Keppler et al., 1976 and 1977). Thus, the CPS instrument is marked by its high time-, energy- and directional-resolutions and by the fact that it is the first instrument deep in interplanetary space to observe protons and electrons as low in energy as 80 and 20 keV, respectively. In combination with the plasma- and magnetic field experiments this CPS experiment is therefore favoured to study "wave-particle-interactions" in interplanetary space well away from the influence of the earth's bow shock.

In this article we want to report on the interaction of two shock-waves and associated magnetic field fluctuations, as observed both by the fluxgate magnetometer (Institut für Geophysik und Meteorologie, Universität Braunschweig) and by the plasma experiment (Max-Planck-Institut für Extraterrestrische Physik, Garching), with low-energy protons, as detected by our CPS experiment during January 6–8, 1975. We shall discuss the influence of these magnetic fluctuations on the energy, the spectral, and the directional distributions of these low-energy protons in view of local and global acceleration mechanisms and interplanetary propagation effects.

Observations of the Interplanetary Medium

During January 6–8, 1975, HELIOS 1 was located at a distance of about 0.92 AU away from the sun, and at a mean earth-sun-probe angle of about 8° east of the earth-sun line. At this time the spaceprobe was therefore well away from the influence of the earth bow shock. According to the observations of the CPS and the high-energy cosmic ray experiments during this period of time, HELIOS 1 was right at the trailing edge of a solar cosmic ray event which was, most probably, associated with a flare that took place on the sun at January 5, 08.00 UT. During the decreasing part of this event both the fluxgate magnetometer and the plasma experiment observed two well defined shock waves: The first one on January 6, at about 20.44 UT, and the second one on January 8, at about 00.22 UT. In Figure 1 we show the locations of HELIOS 1 during January 6–8, 1975, and of the planes of the two shocks in question projected into the ecliptic plane. The associated shock normals are perpendicular to these two planes. Following Neubauer (1977, private communication) the characteristic parameters of the first, the January 6 shock are:

$$\left.\begin{aligned}
\Delta N_p &\approx 6.7\ (\mathrm{cm}^{-3})\\
\Delta V_p &\approx 82.1\ (\mathrm{km\cdot s^{-1}})\\
\Delta F &\approx 5.8\ (\gamma)\\
\varphi_s &\approx 335.2^\circ\\
\theta_s &\approx 30.1^\circ\\
V_s &\approx 625\ \ (\mathrm{km\cdot s^{-1}})\\
\boldsymbol{B}_1\cdot\boldsymbol{n} &\approx 0
\end{aligned}\right\} \qquad (1)$$

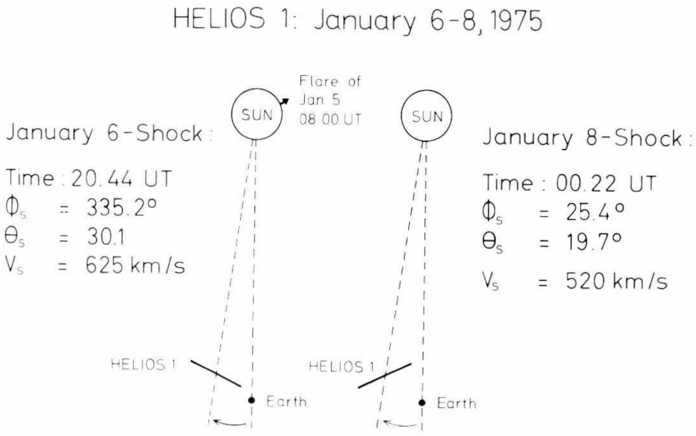

Fig. 1. Location of HELIOS 1, the earth and the two shock-planes during January 6–8, 1975

Thereby N_p and V_p denote the solar wind density and velocity as measured for its proton component, respectively, F the magnitude of the interplanetary magnetic field $\boldsymbol{B}$, $\boldsymbol{n}$ the vector of the shock normal with its angles φ_s and θ_s, where φ (Phi) measures in the ecliptic plane with $\varphi = 0°$ pointing towards the sun, and θ (Theta) out of the ecliptic plane with $\theta = 0°$ in the ecliptic plane, and V_s the shock speed in the direction of its normal. Δ stands for the difference of the pre- (index 1) to the post-shock (index 2) values of the parameters in question. For the second, the January 8 shock Neubauer et al. (1977) quote the following values:

$$\left.\begin{array}{lll} \Delta N_p \approx & 3.12 & (\mathrm{cm}^{-3}) \\ \Delta V_p \approx & 50.0 & (\mathrm{km \cdot s^{-1}}) \\ \Delta F \approx & 5.9 & (\gamma) \\ \varphi_s \approx & 25.4° & \\ \theta_s \approx & 19.7° & \\ V_s \approx & 520 & (\mathrm{km \cdot s^{-1}}) \\ \boldsymbol{B}_1 \cdot \boldsymbol{n} \neq & 0 & \end{array}\right\} \quad (2)$$

Though these two shocks seem to have some similarities (e.g. in their shock speeds and the changes in the proton densities, velocities and the magnitudes of the interplanetary magnetic field across the shocks) there is, however, one very important difference between these two shocks: The first shock-wave is more or less perpendicular while the second one is oblique to the averaged pre-shock field direction. This has, as we shall see, some important consequences for the interplanetary low-energy ions.

In the two lower panels of Figure 2, labelled E2-IGM and E1-MPE, we have plotted 40 s averages of the magnitude of the interplanetary magnetic field (F) in gamma and its angles phi (φ) and theta (θ), and the solar wind velocity (V_p) in km/s and its density (N_p) in cm^{-3}, as measured for the proton component. From these figures it readily follows that these two shock waves

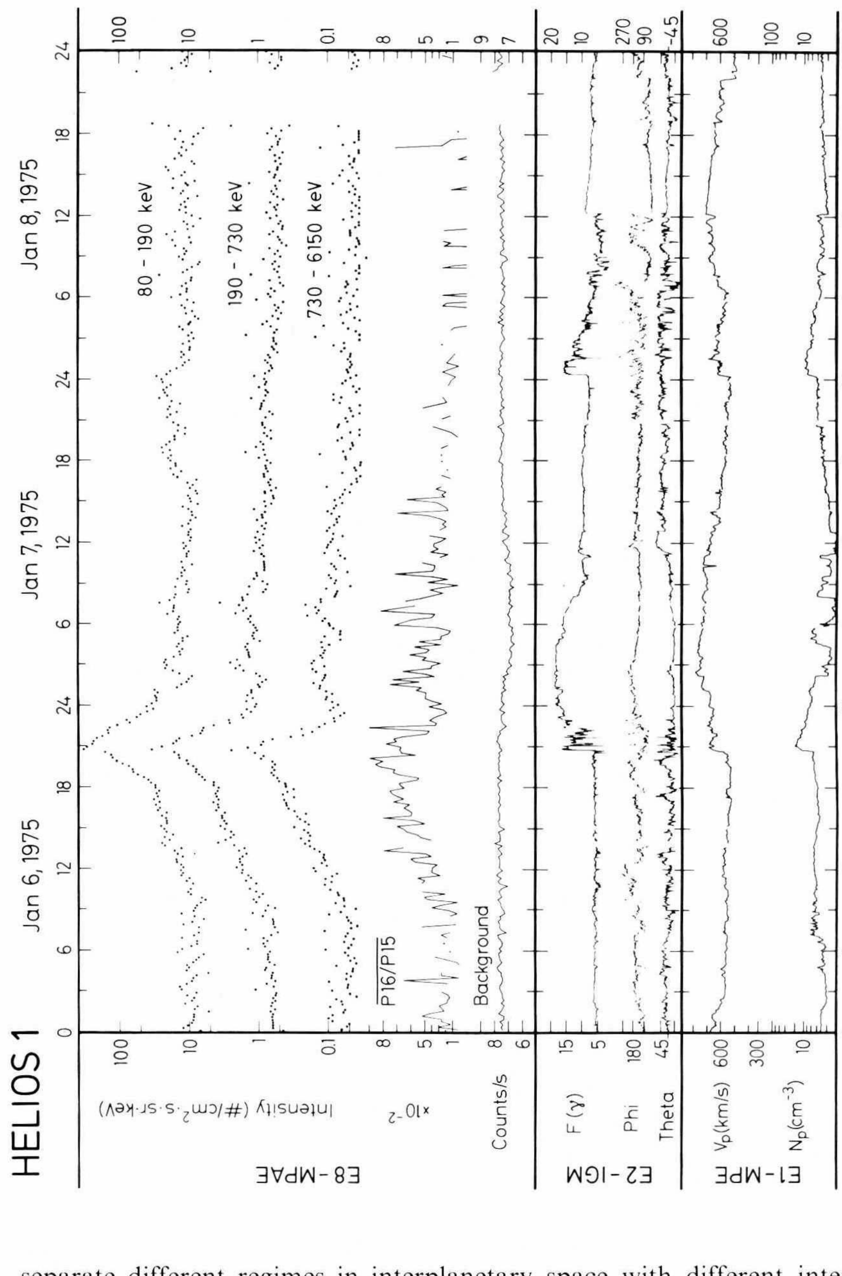

Fig. 2. Time profiles of the ion intensities at different kinetic energies, of the magnitude and the directional angles of the interplanetary magnetic field, and of the solar wind velocity and density during January 6–8, 1975

separate different regimes in interplanetary space with different intensities in the plasma and magnetic-field fluctuations: In the pre-shock regime of the first shock (hour 0–6 of January 6) we find only little fluctuations in the magnetic field magnitude, the solar wind velocity and the proton density. Only for the period from hour 5–9 of January 6 there are some larger (N_p is plotted logarithmically) irregularities in the density. However, taking the directions of the interplanetary magnetic field into account, we first find large directional fluctuations (especially of the angle phi) of increasing amplitudes for a decreasing distance from the first shock front after approximately hour 6. For the subsequent discussion we shall assume that these fluctuations are primarily of Alfvénic type. After we have passed the first shock front we enter into a second regime with enhanced density-fluctuations. These fluctuation could be due to "acoustic" waves most probably generated by the interaction of the shock wave with the pre-shock Alfvén-waves: If the shock normal and the directions of both the background field and the wave-vector of the Alfvén-waves are not co-planar, acoustic waves are generated. This second region extends right up to the tangential discontinuity occuring at 22.18 UT of January 6. After this discontinuity the fluctuations are smoothed out as far as the intensity and the direction of the interplanetary magnetic field are concerned. The interplanetary medium is now characterized by a large gradient in the magnetic field strength of about 12 gamma/5.5 h. At about 11.00 UT of January 7, we enter into a fourth regime which exhibits a similar structure to the pre-shock region of the first shock wave: This regime is again dominated by transverse, directional fluctuations of increasing amplitude. After passing the second shock wave which occurs at 00.22 UT on January 8 there are again superimposed density fluctuations, which last until the tangential discontinuity at 12.13 UT of January 8 is reached. Behind this discontinuity the interplanetary fluctuations are smoothed out nearly instantaneously with a small magnetic field gradient being superimposed.

Observations of Low-Energy Protons

In the upper half of Figure 2 (labelled E8-MPAE) we have plotted 12 min averages of the omnidirectional intensities (particles $\cdot cm^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot keV^{-1}$) of the 80–190 keV, 190–730 keV and the 730–6150 keV protons as observed by the CPS experiment on board HELIOS 1. The intensities of the medium- and the high-energy channel have been multipled by a factor of 10 and 100, respectively. Below these three curves the averaged ration of the ion-energy channels 16 (730–6150 keV) and 15 (585–730 keV) is shown. If the spectral dependence on energy of the protons is known, this ratio is a measure for the proton-to-alpha ratio for alphas with energies greater than about 350 keV/nucl. The fifth and final curve represents the counts/s-time profile of the $4\,\pi$-omnidirectional cosmic-background radiation as observed by the background telescope of the CPS experiment.

From on overall inspection of Figure 2 it readily follows that there is a strong correlation between the different intensity profiles of the low-energy protons and the large-scale fluctuations of the plasma and magnetic field parameters: (1) The intensities of the >80 keV protons peak directly at the first shock front. (2) Around the first shock front the intensities of the three energy intervals indicated are more or less symmetrically distributed. This distribution is narrowest for the >730 keV protons, and relatively wide-spread and asymmetric with a much slower decrease toward the post-shock regime for the 80–190 keV protons. (3) In case of the first shock the intensities of, in particular, the >190 keV protons start to increase already far ahead of the shock front. This increase starts at around 9 o'clock on January 6, and it takes place over exactly that region in space where the magnetic field fluctuations are predominantly Alfvénic. The intensities of the low- and medium-energy protons get flatter and gain local maximum values at around 17.00 h. (4) Combining (2) and (3) we find that the intensity increases in the pre-shock medium of the first shock-wave seem to take place in two separate steps: First, there is the rather slow, long-lasting increase starting well *ahead* of the shock. Secondly, there is the more rapid, steeper well defined increase to the overall maxima *at* the shock front itself. Especially from the low- and medium-energy particles' intensities it follows that this second increase seems to take place shortly after the first increase flattenes off. For the 80–190 keV protons this first-step increase is smallest (a factor of about 3.7 in intensity) and largest for the higher energy ions (~ 11.3), whereas the second-step increase is largest for the low-energy protons (~ 8.5) and smallest for the 730–6150 keV protons (~ 3.1). (5) In case of the second shock wave the situation is more or less inverse: Now, the intensities of the low-energy protons increase ahead of the shock front, whereas there is nearly no effect of the shock wave on the overall tendency of the intensities of the >190 keV protons. This first step increase of the intensity of the low-energy ions starts at about 16.00 h on January 7. Contrary to the first shock-wave there is no pronounced intensity increase associated with the second shock for the >80 keV protons, i.e., there is no pronounced second-step increase. (6) For the 80–190 keV protons, however, the first-step increases ahead of the two shock-waves seem to have one common feature: In both cases the intensities increase by the same factor of about 3.7 over the same period of time of about 7.8 h. (7) Behind the first shock the intensities stay well above background for at least another 10 h. Especially for the >190 keV ions there are, however, several sharp decreases of the corresponding intensities. The reason is that during that time the interplanetary magnetic field turns out of the plane of the ecliptic by 45° and more. Behind the second shock-wave the intensities are roughly equal to the background intensities observed at around 0–6 h on January 6. (8) Between the overall intensity decrease after the first shock and the following increase ahead of the second shock, all intensities gain locally their background values: For the 80–190 keV protons from about 12.00–16.30 h on January 7 and for the 190–730 keV ions from about 14.15–17.45 h. Thus, the two intensity-time histories associated with the two shock-waves are well separated in space and/or time. (9) The intensity-time profile of the P16/P15 ratio indicates that there is an increase of the alpha-to-proton ratio ahead of the first shock. This ratio exhibits roughly the same time history around the first shock-wave as the 730–6150 keV protons. (10) The overall background radiation shows a well defined, long lasting decrease after the first tangential discontinuity has passed the spaceprobe. This is known as a Forbush decrease.

As the background radiation is very smooth and steady and as no extraordinary solar activity has been observed over the time period in question, we may conclude that the strong correlation mentioned above is due to interactions of the ions with the shock waves and associated fluctuations. Thus, in order to study the spectral dependence of the protons on energy, the anisotropy and the direction of anisotropy, we have to transform the corresponding intensities, energies and characteristic angular directions from the spacecraft into the solar wind frame. As there are observations available in 15 energy intervals in the 80–730 keV range, we are able to undertake the most general, non-linear Compton-Getting transformation between the two frames by making no assumptions about, for instance, the spectral shape, the dependence of the spectral index γ on the direction etc. After performing this transformation we calculated the value A of the anisotropy from the maximum (I_{max}) and minimum (I_{min}) intensities of the angular directions respectively, via the equation

$$A=(I_{max}-I_{min})/(I_{max}+I_{min}). \quad (3)$$

As the CPS instrument is pointing in the ecliptic plane, the directional information (intensity *vs.* direction) can be transformed into the angular information (intensity *vs.* ecliptic angle φ (Phi)). Thus, we are able to plot intensity *vs.* φ and time. Determining then the overall omnidirectional intensities of the 15 energy-channels, we are able to calculate the spectral index γ by assuming a power-law dependence of the intensity on energy and by applying a least-squares fit procedure.

In Figures 3a and b we have plotted the 12 minutes averaged values of the intensities J (protons/$cm^2 \cdot s \cdot sr \cdot keV$) of 100 keV protons *vs.* the ecliptic angle φ and time t in the upper halves, and of the values A of the anisotropy as defined by equation (3) *vs.* time t in the lower halves. For the directional plots of the intensities (upper halves) we have subjected the J-values to a grey-shading scale of 6 settings, ranging from black (lowest intensities) to white (highest intensities). On the right hand sides we have indicated the corresponding threshold values. As the intensities associated with the first shock are, on the average, much higher than for the second shock-wave, we had to make two separate plots in order to show the effects. Figure 4 shows the distributions of the magnitude and angles Phi and Theta associated with the interplanetary magnetic field $\boldsymbol{B}$ (see Fig. 1) and of the exponent (spectral index) γ for those time-periods around the two shock-waves where the intensities are above their background values.

From these three Figures we find: (11) In case of the first shock (Fig. 3) the value of the anisotropy starts to increase and to gain overall higher values in front of the shock wave, and to decrease more or less abruptly across the shock front itself. In the pre- and post-shock regions the anisotropy is rather high. However, it exhibits some longer-lasting depression around 9–12 o'clock on January 6. This is about the time interval where the interplanetary magnetic field starts to fluctuate in its direction, especially in the angle φ. (12) In case of the second shock-wave (Fig. 3b) the anisotropy increase is not very much pronouned, nor its decrease across the shock front itself. In the pre-shock regime the anisotropy stays at about 0.8 and is therefore rather high. (13) Turning to the directional plots of the anisotropy, we find around the first shock-wave: There is well defined bi-directional anisotropy in the pre-shock region from hour 0 to about hour 17 on January 6. Note the enormous difference in the intensity values, ranging from below 5 up to over 200 protons/

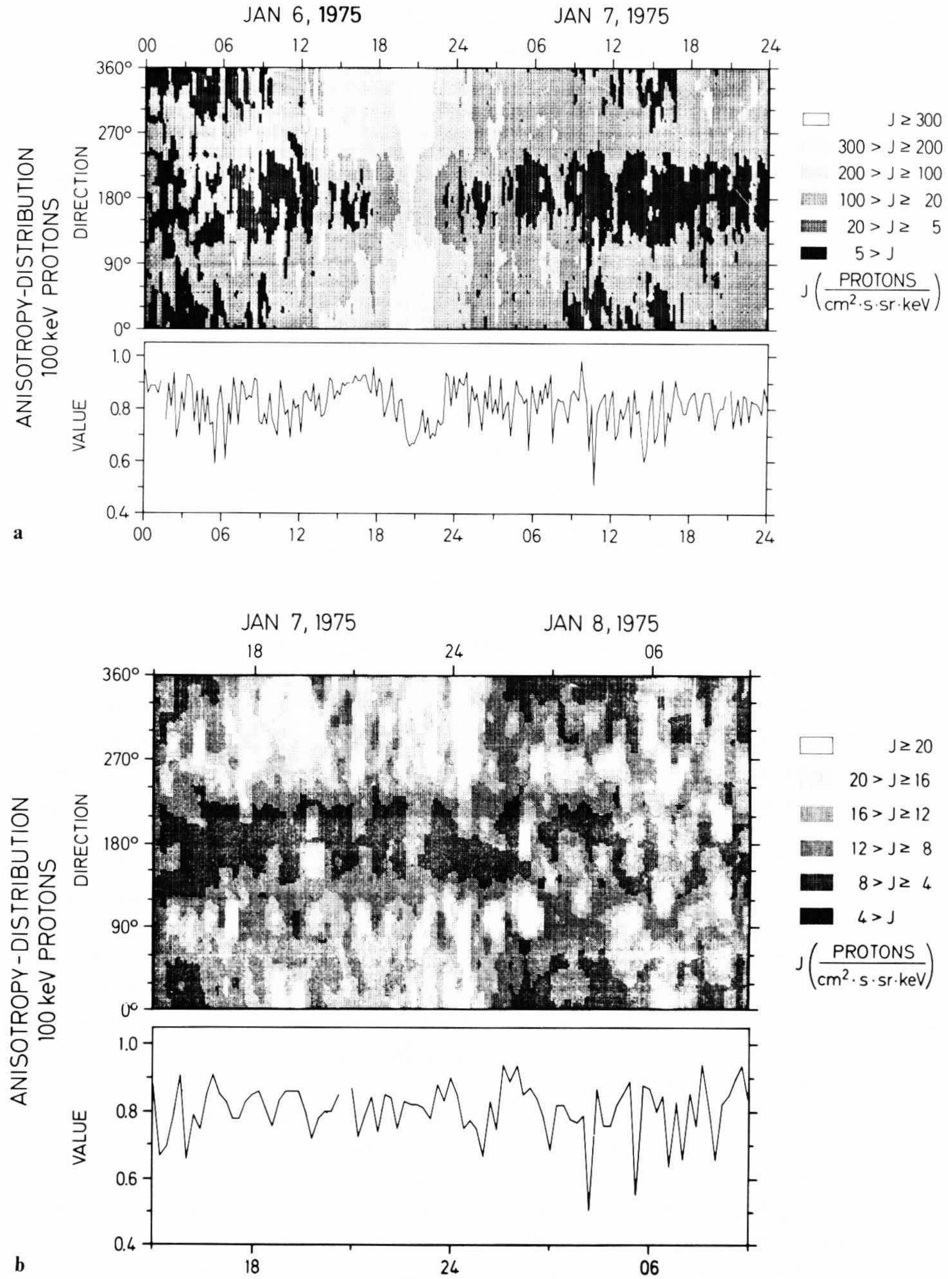

Fig. 3a and b. Distribution of the directional anisotropy (intensity *vs.* time and ecliptic angle φ) and the anisotropy value *vs.* time for 100 keV protons transformed into the solar wind frame around the two shock-waves observed on January 6 and 8, 1975

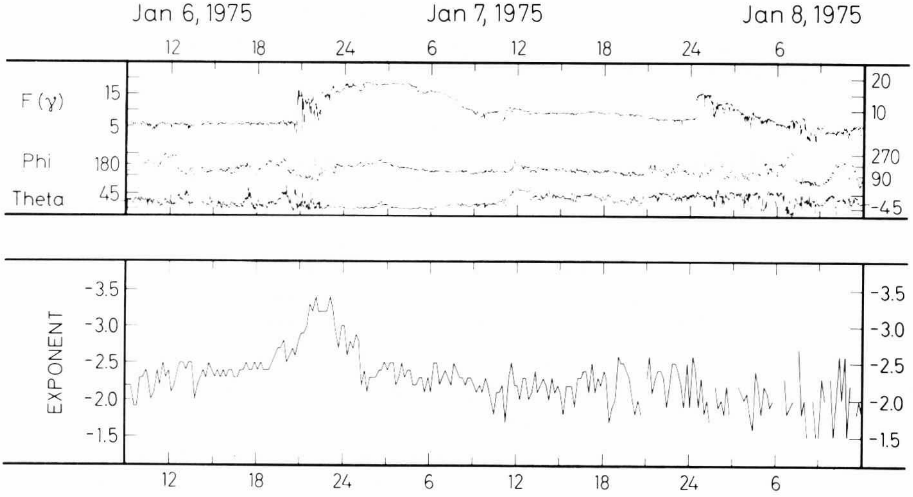

Fig. 4. Time profiles of the magnitude and the directional angles of the interplanetary magnetic field, and of the spectral exponent γ determined by a least-squares fit procedure of the transformed omnidierectional intensities of 16 energy-channels ranging from 80–6150 keV

$cm^2 \cdot s \cdot sr \cdot keV$. Over this period of time the maximum fluxes are separated by about 180°, indicating a flow of the 100 keV protons towards and away from the shock front at the same time. This type of a strong, bi-directional anisotropy is also found in the post-shock region from about hour 23 onwards. It should be noted that these two bi-directional regimes coincide with the pre- and post-shock intensity distributions of the 80–190 keV ions in Figure 2. Over that period of time, i.e., from hours 17–23, where in Figure 2 the low-energy protons exhibit their second-step increase to their overall maximum, their anisotropy distribution becomes more isotropic, and therefore the value of their anisotropy decreases. (14) In case of the second shock wave we again find a rather strong, bi-directional anisotropy distribution in front and behind the shock plane. The directions of the corresponding maximum particle fluxes are again separated by approximately 180°, i.e., the low-energy protons are streaming towards and away from the shock plane at the same time. Around the shock front itself the distribution of the 100 keV protons again gets more isotropic. (15) We want to mention that for 300 keV protons, i.e., for particles belonging to the second of our three energy intervals depicted in Figure 2, we find roughly the same overall distributions around the two shocks what the directional anisotropy as well as the anisotropy value is concerned. (16) Turning finally to Figure 4 we find for the spectral index γ that it gains overall higher values of around 2.4 in the pre-shock regime of the first shock at around 14.00 h on January 6, and of about 2.3 in the pre-shock region from around hours 1–9 of January 7. Across the shock front itself γ increases only slightly. Its absolute maximum value of 3.4, however, the spectral index reaches well *behind* the shock front at about hours 22.00–23.30. In case of the second shock-wave we can state that γ exhibits no systematic changes in front, at, or behind the shock. However, it should be noted that the mean overall value of γ drops from about 2.2 to a value of 2.0 across the shock plane with a change in the maximum-to-minium values of about 2.6 to 1.7.

Discussions

According to the theory of, e.g., Scholer and Morfill (1975) and Morfill and Scholer (1977a) (see also references cited in there), cosmic ray particles can be accelerated by interaction with oblique shock waves due to the induced electric field in the shock front (first order Fermi acceleration). If the particles' mean free path in the pre-shock region of the shock is small enough, then a repeated interaction with the shock front and thus a repeated acceleration can take place, while the shock is propagating from the sun out to 1 AU. The authors have shown that already 5–10 interactions per AU with a normal strong shock wave and relatively *high* diffusion coefficients of the order of $(2–5)\times 10^{20}\ \mathrm{cm}^2\cdot\mathrm{s}^{-1}$ for the pre-shock region can already accelerate protons from thermal energies to some hundreds of keV. It is stressed that this type of acceleration is by more than an order of magnitude more effective than any pile-up process ahead of shock fronts discussed by, e.g., Palmer (1972). Monte-Carlo model calculations have led to the following results: First, the repeated acceleration leads to a maximum intensity of the accelerated particles which occurs at some time τ (hour) *before* the shock arrives. Roughly it is $\tau \propto 1/V_s$ and energy-independent, where V_s is the shock velocity. Then the intensity decreases rather rapidly behind the shock by about an order of magnitude within one hour. Second, the actual maximum value of the intensity depends on the value of the diffusion coefficient in the pre-shock region. If this value is, e.g., too high the particles being accelerated once can easily 'disappear' into interplanetary space. Third, the anisotropy value A increases in front of the shock-wave and then decreases across the shock front itself. Fourth, due to the acceleration process itself the anisotropy distribution in the pre-shock regime should be bi-directional with a difference of 180° in the streaming directions of particles of maximum intensities, indicating that particles are propagating towards and away from the shock at the same time. Particle increases due to this type of acceleration process are sometimes called 'ESP (*E*nergetic *S*torm *P*article) Events'. From the discussion on the ESP-acceleration mechanism it directly follows that it has to operate for a rather long time (t_{ESP}) in order to produce significant increases in the particles' intensity to be observed above certain energy-thresholds (e.g., 80 keV for our CPS instrument) and well above the instrumental background.

Following Sarris and Van Allen (1974) a very intensive acceleration of charged particles can take place, if the shock wave is nearly perpendicular, i.e., if the pre-shock magnetic field is almost parallel to the shock surface itself. Schindler (1965) has shown that this acceleration is not of the type of first or second order Fermi acceleration. In this case low-energy protons, e.g., can be accelerated nearly instantaneously up to ε-times their initial energy, where $\varepsilon = B_2/B_1$ is the ratio of the averaged magnetic strengths in the post- and pre-shock regions, respectively. If $t_{\parallel}$ is the time that the pre-shock magnetic field stays parallel to the shock front, and if t is the time spent by an ion in the shock front, then the only restraint for this fast and strong acceleration mechanism is that t should be less than $t_{\parallel}$. Then for the peak-to-background (p/b) intensities one roughly finds $p/b = \varepsilon^{\gamma+1}$, where γ is the ion spectral index. As the time t is roughly proportional to the particles' initial rigidity, this mechanism is strongest for the low-energy ions. Due to fluctuations in the direction of the interplanetary magnetic field in the pre-shock regime, both the background field and the shock front will stay parallel only for a short time. Thus, this acceleration mechanism is only a local effect, and it will mostly operate only for a short time (t_{SSE}). Particle increases due to this kind of acceleration are called "Shock-Spike Events". From the discussions above it clearly follows that $t_{SSE} \ll t_{ESP}$.

Studying energetic charged particles in association with interplanetary oblique shocks one rather often finds increases in their intensities in the post-shock regimes. According to Morfill and Scholer (1977b) these 'Post-Shock Events' could be due to the following post-shock acceleration processes: First, after a shock wave there are out- and inwardly propagating waves present. Thus, there is a strong possibility of second order Fermi acceleration behind shock waves. Second, there are very often more acoustic waves present after a shock than in the quiet solar wind in front of the shock. This could lead to particle acceleration by nonlinear wave-particle interactions. Third, due to an enhanced gradient of the solar wind velocity after the shock front the adiabatic decceleration could be much smaller in the post-shock regime. Another, different theory on the formation of these post-shock events has been discussed by Sarris and Van Allen (1974): Whenever an oblique shock becomes a perpendicular one, particles are instantaneously accelerated in the way discussed above. Due to the directional fluctuations of the post-shock magnetic field these accelerated particles very easily are able to penetrate into the post-shock regime and to cause an increase in the overall particles' intensity. However, there should be at least two differences in the mechanisms mentioned: First, the time-scale of the first process to operate (t_{PSE1}) and of the second one (t_{PSE2}) should be such that $t_{PSE2} \ll t_{PSE1}$. Second, if the first process is primarily a Fermi process, then the directional anisotropy should be bi-directional for the first mechanism, but primarily uni-directional for the second one.

Combining the observational results for the intensity-, the anisotropy-, and the spectral index-time profiles of the >80 keV ions in Figures 2–4 together with the theoretical studies summarized above, we propose that the particles' intensity distributions during January 6–8, 1975, can be understood in terms of classical ESP-, Shock-Spike-, and Post-Shock-Events in the following sense: (A), the first-step intensity increases *in front* of the two shock waves are ESP-Events in the sense discussed above. (B), the second-step intensity increases *at* the first shock-wave a Shock-Spike-Event in the sense mentioned before. (C), the high, but overall decreasing intensities behind the first shock are due to post-shock acceleration mechanisms. In the following three sections we shall briefly list our arguments and draw some implications:

(A) The intensity of the >730 keV protons starts to increase already 10 h before the first shock arrives, or of the >80 keV ions at least 8 h in front of the second shock. In both cases there is a well defined *bi-directional* anisotropy with a separation by 180°. This indicates that protons are propagating towards the shocks and away from them into the pre-shock regions at the same time. We want to emphasize that this holds even for the 100 keV protons. Thus, even for these low energies some kind of "diffusive" process has to take place at least in the pre-shock regimes. In case of the first shock the anisotropy value does increase in front of the shock-wave, and does decrease drastically across the shock front. We find relatively high values of the spectral index of ~2.4 over the time-periods in question, which might also indicate that some kind of acceleration takes place. At least for the 80–730 keV protons we find some local intensity maxima $\tau \approx 4$–5 h in front of the first shock-wave. Using the relation of Morfill and Scholer, we find, because of equation (1), $\tau \approx 5.6$ h, and therefore some coincidence. However, in contrast to theory the τ-values are not energy-independent: The τ-value for the 730–6150 keV protons is much smaller than for the 80–730 keV ions. We believe that this is due to a strong energy-dependence of the diffusion coefficient in the pre-shock medium in the sense that this diffusion coefficient increases for decreasing energies. That this could be indeed the case can also be deduced from the different values for the p/b-ratios for the three energy-intervals depicted in Figure 2: In accordance to theory, we find higher values ($p/b \approx 11.3$) for the 730–6150 keV protons, however, only $p/b \approx 3.7$ for the 80–730 keV ions (for a second argument for our hypothesis see also (B)). In case of the second shock the situation is inverse: Now the ESP-type behaviour increases for decreasing energies. Thus, the magnetic fluctuations in front of the second shock should be such that the particles' mean free paths should be smaller for the lower-energy protons. Another possibility could be that the second shock was formed somewhere between sun and earth, and therefore did not last long enough to accelerate thermal particles to energies much larger than 200 keV.

(B) The intensities of protons of all energies >80 keV peak directly at the shock. The anisotropy gets omni-directional. In accordance with the theory the shock-spike acceleration is rigidity dependent: We find larger intensity increases for the low-energy protons with $p/b \approx 8.5$ for the 80–190 keV particles than for the higher-energy ions, for which $p/b \approx 3.1$ in the 730–6150 keV range. Using Figures 2 and 4 we calculated a value for p/b predicted by theory of ~8.4, which is in excellent agreement with the value for the low-energy protons. The more or less symmetric intensity distributions on the two sides of the shock could be due to the following effect: The accelerated particles can penetrate into the up- and down-stream medium whenever, due to the large-amplitude directional fluctuations of the magnetic field, both the field direction and the direction of the shock front are oblique and no longer parallel to each other. These particles would then only steam away from the shock, i.e., they would be characterized by an uni-directional anisotropy distribution. Following Figure 3a the clear bi-directional anisotropy gets indeed mixed up around 18.00 h when, according to Figure 2, we find the onset of the second-step increase of the intensity of the 80–190 keV protons. As was stated in (2), the intensity distributions directly at the first shock are much broader for the low- than for the high-energy protons. Again (see also (A)) we believe that this is due to an energy-dependence of the pre- and post-shock diffusion coefficients in the sense, that they are larger for the 80–190 keV than for the 730–6150 keV ions.

(C) If the first-step particles' increases in front of the first shock are due to an ESP event, then the intensities do not, as they should according to theory, decrease by an order of magnitude within one hour behind the shock-wave. Quite contrary, at least for the 80–190 keV protons the post-shock intensity remains as high as for the maximum value of the ESP event itself. Thus, some particle release into the post-shock regime and/or some type of post-shock acceleration has to take place. We believe that at least about the time of observation the acceleration hypothesis should be favoured: First, the increasing value of γ could be some index for such a mechanism. Second, the clear *bi-directionality* of the anisotropy over this region (Fig. 3a) is a strong argument for a Fermi-type acceleration mechanism in the post-shock region. As was stated before (7) the several sharp decreases of the intensities are due to the fact that during these time-intervals the interplanetary magnetic field turns out of the ecliptic plane by 45° and therefore out of the cone of acceptance of our instrument.

Acknowledgements. We are very grateful to Prof. F. Neubauer and Dr. G. Musmann (IGM, Braunschweig) and Drs. H. Rosenbauer and R. Schwenn (MPE, Garching) for submitting the magnetic field and plasma observations prior to publication. We also want to thank Drs. K. Richter and M. Schüßler for their assistance.

This work was supported in part by the Bundesministerium für Forschung und Technologie, grant WRS 10/8.

References

Keppler, E., Richter, A.K., Richter, K., Umlauft, G., Wilken, B., Williams, D.: A Survey on Measurements of Medium Energy Protons and Electrons obtained with the Particle Spectrometer E8 on Board of HELIOS, J. Geophys., this issue, 1977

Keppler, E., Wilken, B., Richter, K., Umlauft, G., Fischer, K., Winterhoff, H.P.: Ein Spektrometer für geladene Teilchen mittlerer Energie: Experiment E8 HELIOS, BMFT-FB W 76-14, 1976

Morfill, G.E., Scholer, M.: Influence of Interplanetary Shocks on Solar Particle Events, Astrophys. Space Sci. **46**, 73–86, 1977a

Morfill, G.E., Scholer, M.: Der Diffusionskoeffizient hinter interplanetaren Stoßwellen, Frühjahrstagung der Arbeitsgemeinschaft Extraterrestrische Physik, Braunschweig, Vortrag C8-1, 1977b

Neubauer, F.M., Musmann, G., Dehmel, G.: Fast Magnetic Fluctuations in the Solar Wind: HELIOS 1, J. Geophys. Res., in press, 1977

Palmer, I.P.: Shock Wave Effects in Solar Cosmic Ray Events, Solar Phys. **27**, 466–477, 1972

Sarris, E.T., van Allen, J.A.: Effects of Interplanetary Shock Waves on Energetic Charged Particles, J. Geophys. Res. **79**, 4157–4173, 1974

Schindler, K.: Adiabatic Orbits in Discontinuous Fields, J. Math. Phys. **6**, 313–321, 1965

Scholer, M., Morfill, G.E.: Simulation of Solar Flare Particle Interaction with Interplanetary Shock Waves, Solar Phys. **45**, 227–240, 1975

Received January 31, 1977; Revised Version June 14, 1977