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Suprathermal proton and α-particle bursts (E/q = 6.5–225 keV/e) observed by the WIND-, ACE- and IMP8–S/C during depressions of the interplanetary magnetic field

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Abstract. The present study deals with suprathermal proton (E/q = 6.5−225 keV/e) and α-particle bursts measured by the WIND-SMS experiment in the interplanetary space. They reach up to ∼5–20 times the solar wind speed and last from a few minutes up to ∼30 min. Measurements obtained simultaneously by the Solar Wind Ion Composition Sensor SWICS (E/q = 0.5−31.5 keV/e) were also available for this study, as well as magnetic field and particle data recorded by ACE near the Libration point L1 and the IMP8-S/C near the Earth. In order to exclude particles escaping from the magnetosphere or accelerated by the Earth's bow shock, interplanetary shocks, coronal mass ejections and corotating interaction regions, we selected ion bursts which were associated with a distinct decrease in the interplanetary magnetic field magnitude and with changes in the azimuthal and tangential field direction. Such changes have been known for a long time as magnetic holes or field depressions. We interpret these signatures as a manifestation of a reconnection process in the interplanetary space near the heliospheric current sheet at about 1 AU distance from the Sun and show for the first time that thermal particles can be accelerated up to ∼100 keV/e. The suprathermal particles are most likely accelerated in the electric field of the X-line. Inductive electric fields caused by changes in the field magnitude could also be responsible for the particle acceleration.

Key words. solar wind

1. Introduction

In this paper particle bursts (increases in the intensity and energy of the particles) will be studied, as observed by the Solar Wind Ion Composition Sensor SWICS (0.5–31.5 keV/e) and the Suprathermal Ion Composition Sensor STICS (6.5–225 keV/e) on the WIND-S/C during distinct decreases in the magnetic field magnitude as measured by the MFI experiment. The suprathermal bursts usually have a duration of minutes, whereas the thermal bursts can last a few hours. In this study all bursts which are accelerated in the magnetosphere (Sarris et al. 1976) or at the bow shock (Mitchell et al. 1983; Haggerty et al. 2000), as well as particles fluxes caused by shocks and corotating interaction regions are excluded. Only particle bursts associated with distinct decreases in the magnetic field magnitude and with changes in the azimuthal and tangential field direction will be considered, which we interpret as the reconnection process. Magnetic field line merging in the interplanetary space has been described for the first time by Schindler (1972). Bavassano et al. (1976) used Pioneer 8 magnetometer observations to study the field line merging process. In such a process, reconnected oppositely directed magnetic field lines near the heliospheric current sheet, caused by a lateral pressure, form an X-line, whereby plasma is accelerated in both sunward and antisunward directions. The electric field of the formed X-line accelerates particles to suprathermal energies. The signatures show a decrease in the magnetic field magnitude of up to 30 min in duration, with a sudden change in the azimuthal field direction by ∼180° and a change in the inclination angle from north to south or vice versa. Further examples for reconnection in the interplanetary magnetic field or just depressions in the magnetic field were presented by Turner et al. (1977), Burlaga & Lemaire (1978), McComas et al. (1994), Winterhalter et al. (2000), Collier et al. (2001), Fränz et al. (2000), Chisham et al. (2000), Neugebauer et al. (2001), Zurbuchen et al. (2001). The purpose of the present paper is to study thermal and suprathermal particle bursts observed by the WIND and other S/C during magnetic field depressions. Areas of interest include their acceleration mechanism, flux, energy, ion composition, angular distribution and the dynamic behavior of the reconnecting magnetic field structure.

2. Experiment description

The SWICS (E/q = 0.5−31.5 keV/e) and the STICS sensor (E/q = 6.5−225 keV/e) were already described by Gloeckler et al. (1995). Both sensors use an electrostatic analyser at the

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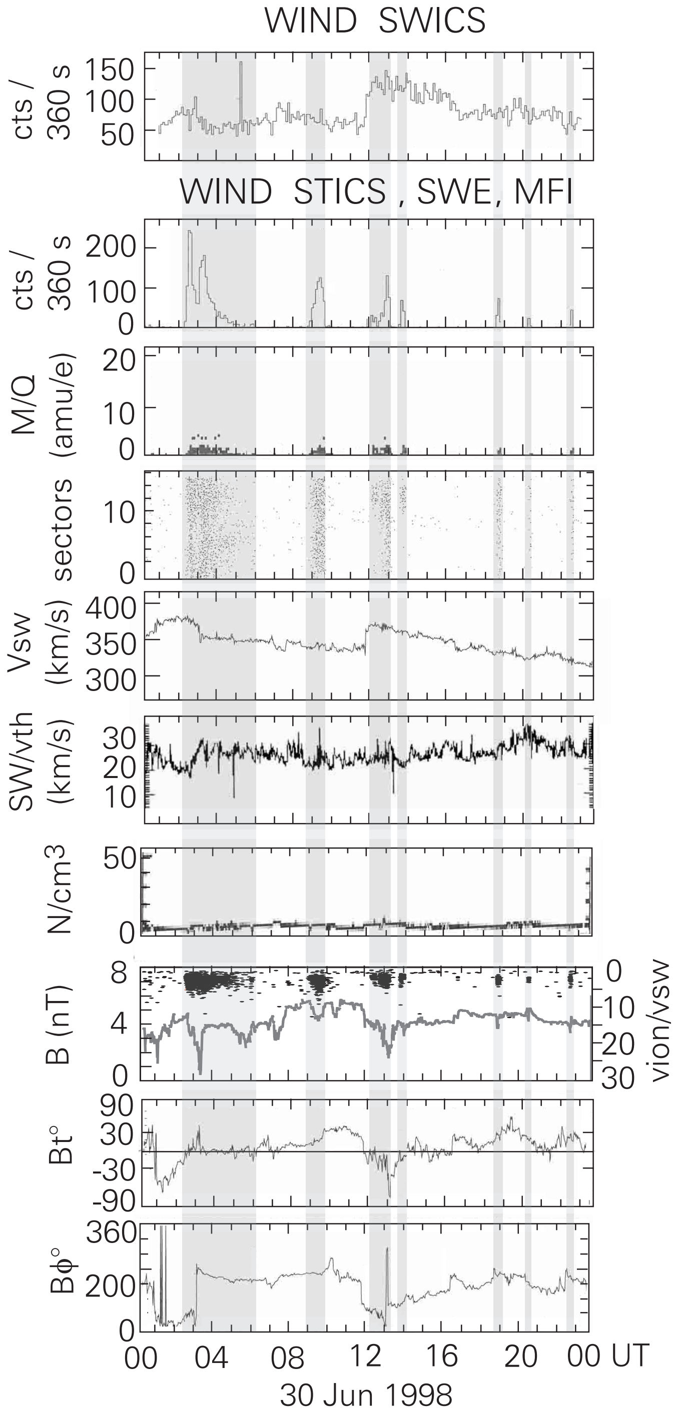

Fig. 1. From top to bottom are shown: SWICS (0.5–31.5 keV/e), STICS (6.5–225 keV/e) ion count rates, M/Q =mass/charge ratio, count rate in the sectors 0–15, V_{sw} = solar wind velocity, $sw\,v_{\mathrm{th}}$ = solar wind thermal velocity, N/cm^3 = density, B = magnetic field magnitude together with the ratio $V_{\mathrm{ion}}/V_{\mathrm{sw}}$, B_{t} = tangential, B_ϕ = azimuthal field direction. Shadowed are suprathermal (6.5–225 keV/e) particle bursts. Two distinct decreases in the magnetic field magnitude B and suprathermal bursts appeared at ~3:10 and ~13:10 UT. The STICS count rates consist of H^+, He^{++} and heavier ions. The intensity increases of (0.5–31.5 keV/e) ions and the small increase in V_{sw} by 30–50 km s^{-1} at ~1:00 and ~12:00 UT seem to also be caused by the reconnection process. B_{t} and B_ϕ indicate that the heliospheric current sheet was crossed. The WIND-S/C was near the Earth.

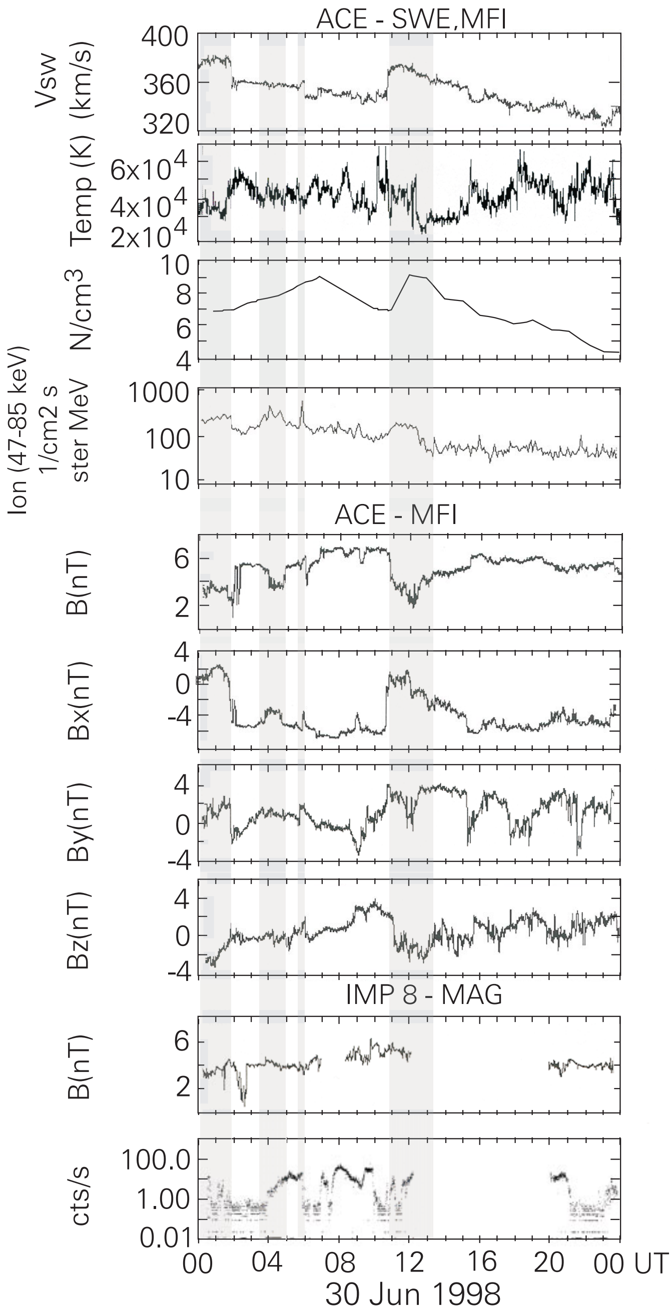

Fig. 2. Simultaneously obtained solar wind ion velocity, temperature, density, energetic ions (47–85 keV) and magnetic field measurements of the ACE-S/C, located in the libration point L1 and IMP8, magnetic field and ion measurements (>15 keV). The solar wind and the (47–85 keV) ions are obviously accelerated by a similar magnetic field structure, however, about 1 h earlier than near the Earth.

entrance, a time-of-flight measurement for the ions and a measurement of their rest energy by a semiconductor detector. In addition, the SWICS sensor applies an internal acceleration voltage for the ions and, therefore, has a lower threshold.

3. Observations

Since its launch on 1 Nov. 1994, the SMS-experiment on the WIND-S/C observed numerous short-lived bursts

($E/q = 6.5$–225 keV/e) when the ratio $V_{\mathrm{ion}}/V_{\mathrm{sw}}$ (ion velocity/solar wind velocity) is plotted vs. time. Such bursts appear superimposed on CIR and shock accelerated particle fluxes, and also superimposed on the quiet background flux, associated with and without a distinct decrease in the interplanetary magnetic field magnitude. We selected here only bursts which were associated with a distinct decrease in the magnetic field magnitude. The selection criterion was $\Delta B = 2$–6 nT, $\Delta B_{\mathrm{t}} \sim \pm 30°$, $\Delta B_{\phi} \sim \pm 180°$. In Fig. 1, SWICS (0.5–31.5 keV/e) and STICS measurements (6.5–225 keV/e) are shown, as well as the solar wind velocity and magnetic field measurements. The panels (from top to bottom) display the count rate of thermal ($E/q = 0.5$–31.5 keV/e) and suprathermal ($E/q = 6.5$–225 keV/e) ions, the mass/charge ratio M/Q, the particle distribution in the sectors 0–15, (sectors 9, 10 point toward the Sun, 1, 2 in antisunward direction, 5, 6 toward $+Y_{\mathrm{se}}$ and 13, 14 in $-Y_{\mathrm{se}}$ direction), the solar wind velocity V_{sw} measured by the SWE experiment, the thermal velocity and density of the solar wind. We then show the magnetic field magnitude in nT, together with the ratio $V_{\mathrm{ion}}/V_{\mathrm{sw}}$, the tangential and azimuthal field direction in solar ecliptic coordinates. From Fig. 1 we conclude that between ~03:00 and ~13:05 UT, the magnetic field magnitude showed two minima. The tangential and the azimuthal field direction changed dramatically at ~0:55, ~3:10, ~11:55 and ~13:05 UT on 30 June 1998 and then returned to the old direction. Proton and α-particle bursts were associated with the magnetic field depressions. The solar wind velocity was slightly increased by 30–50 km s^{-1} between 00:00–3:00 UT and 12:00 and 24:00 UT. The increase could also be observed with SWICS (upper panel, $E/q = 0.5$–31.5 keV/e). The SWICS sensor with its lower energy threshold detected accelerated solar wind ions somewhat earlier than the STICS sensor. The suprathermal ions reached ~10 times the solar wind speed during a second acceleration process. The thermal velocity and the density show only small variations. Thus, the two decreases in the magnetic field magnitude obviously caused two different acceleration processes. The sector measurements reveal a nearly isotropic distribution, whereas the second burst group also shows an anisotropic behavior (flux only in sectors 11–15). The burst observed by STICS from 9:00 to 10:00 UT is also associated with a B-decrease. A part of that burst could be of magnetospheric origin (see Haggerty et al. 2000). The two burst groups presented in Fig. 1 indicate that the reconnection process in the magnetic field started with an acceleration of the solar wind plasma (>0.5 keV/e). In a second step energies of 6.5–100 kev/e are reached, as the STICS sensor reveals. The position of the WIND-S/C was at $X_{\mathrm{se}} \sim +20R_{\mathrm{e}}$ and $Y_{\mathrm{se}} \sim +50R_{\mathrm{e}}$ during the bursts shown in Fig. 1.

In Fig. 2 measurements of the ACE-S/C, located in the libration point L1, are depicted together with magnetic field magnitude measurements of IMP8 ($X_{\mathrm{se}} \sim 35R_{\mathrm{e}}$, $Y_{\mathrm{se}} \sim 10R_{\mathrm{e}}$) and ion measurements of IMP8 for the same event. The panels display (from top to bottom) the solar wind velocity measured by ACE (located in the libration point), temperature in Kelvin, density, flux of 47–85 keV ions, magnetic field magnitude B and the components B_x, B_y, B_z. In the lower two panels the magnetic field magnitude B and >15 keV-ions measured by IMP8 near the Earth are displayed. The magnetic field decreases and the production of ions (45–85 keV), as well as the density and temperature variation of the solar wind plasma, appear about 1 hour earlier in the libration point than near the Earth. Thus, one could conclude that the reconnection process in the magnetic field lasted at least ~1 hour or that it started again when the solar wind with the magnetic field reached the Earth.

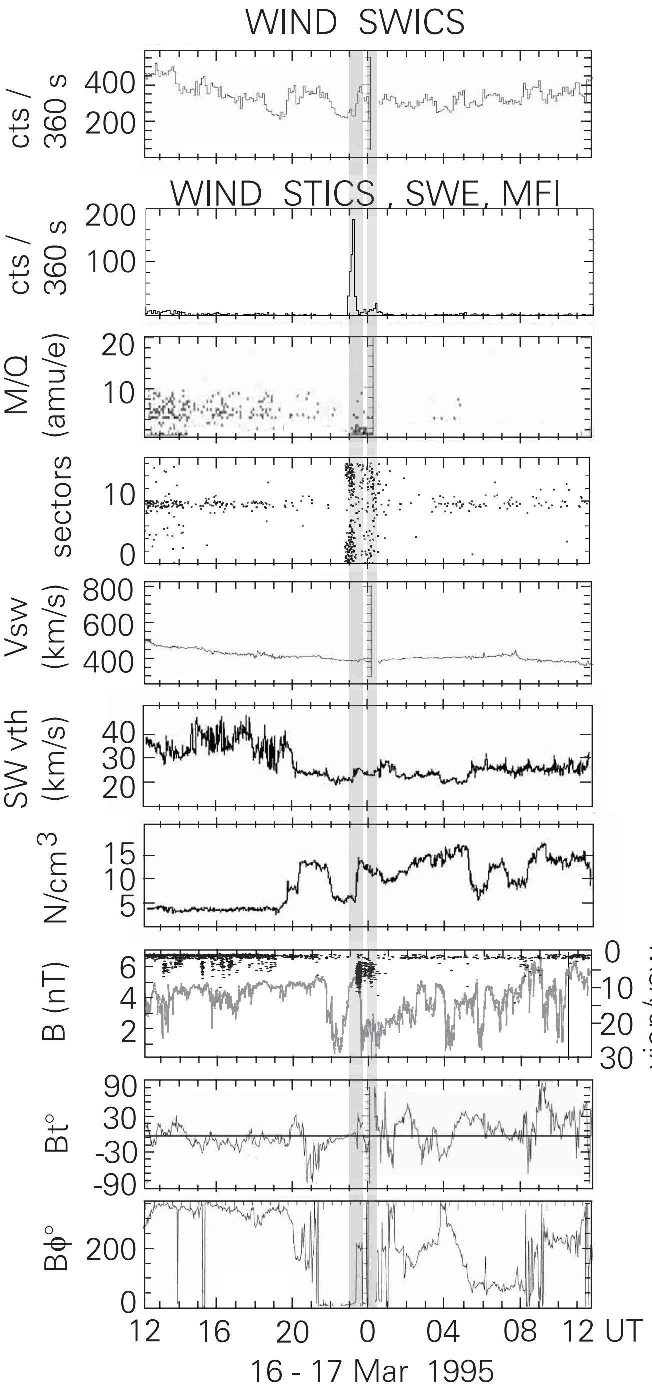

Fig. 3. The same as Fig. 1 for 16–17 March 1995. A two-step decrease of B and particle bursts were measured between 16 March, ~20:00 UT and 17 March, ~4:00 UT 1995. The $E/q = 6.5$–225 keV/e ions showed an intensity increase together with the second B-decrease. Also presented are the thermal velocity and the density of the solar wind plasma. The WIND-S/C was in the libration point L1.

Figure 3 presents two bursts observed by WIND in the libration point L1 from 16–17 March 1995. One sees two decreases in the field magnitude B and changes in the tangential and azimuthal field direction between 16 March, ~20:00 UT and 17 March, ~5:00 UT 1995. The SWICS sensor shows a broad and a small burst. Only the second one also consisted of protons which reached about 10 times the solar wind speed, as can be seen from the STICS sensor. The sector measurements let us conclude that the first burst observed by STICS probably started antisunward from the WIND-S/C, since the intensity increase was observed in sectors 0–6 and 12–15 which indicate a particle population trapped on field lines. The gyroradii of 10, 50 and 100 keV protons in a 5 nT field are ~2900, ~6400 and ~9100 km, respectively. The second burst (Fig. 3) appeared sunward from WIND, since the flux increase was measured in the sectors 6–15 which point mainly in a sunward direction. From Fig. 3 it can be seen that the plasma density increases during the reconnection process but not the thermal velocity of the ions. A comparison of the magnetic field measurements by WIND located in the libration point L1 and IMP8 near the Earth revealed again a delay of ~1 hour (not shown as a figure).

The third example (Fig. 4) shows again two decreases in the magnetic field magnitude on 23 April 1997 between ~10:12 UT and ~13:12 UT. The WIND-S/C was in the libration point L1. The SWICS sensor measured a broad single peak during that interval, while STICS detected a single short burst at the end of that interval. The plasma density, but not the thermal velocity, increased during this reconnection event. The sector measurements indicate isotropy for the burst at ~13:00 UT and an anistropy for the small burst at ~0:30 UT which is also caused by a small B-decrease. The fluxes in sectors 9 and 10 result from solar particles and 4He$^+$ as the M/Q panel of Fig. 4 demonstrates. IMP8 measurements from 23 April 1997 are not available for a comparison.

In Fig. 5 a magnetic field depression is shown which was classified by Zurbuchen et al. (2001) as a "microscale magnetic hole" observed by ACE near the heliospheric current sheet. The authors suggest that such holes are formed by reconnection close to the Sun. Figure 5 presents, from top to the bottom, thermal (0.5–31.5 keV/e) and suprathermal (6.5–225 keV/e) ions measured by WIND near the heliospheric current sheet in the libration point L1. Then the M/Q ratios, the sector measurements, the solar wind velocity, thermal velocity and density follows. The last three panels show magnetic field magnitude B, together with the ratio $V_{\text{ion}}/V_{\text{sw}}$, the tangential and azimuthal field direction. It can be seen that this magnetic field depression is associated with an increase in the thermal ion (0.5–31.5 keV/e) count rate, the solar wind velocity V_{sw}, the thermal velocity and density. Suprathermal particles (6.5–31.5 keV/e) appear as a short-lived peak of isotropic distribution and a velocity of ~12 times the solar wind velocity at the end of the long lasting field depression. Simultaneously, the magnetic field magnitude shows a small depression of ~5 nT and the azimuthal direction changes ~180°. All particle bursts presented in Figs. 1–5 were also observed by the WIND 3D Plasma experiment (R. P. Lin et al., see CDA Web Wi_K03DP).

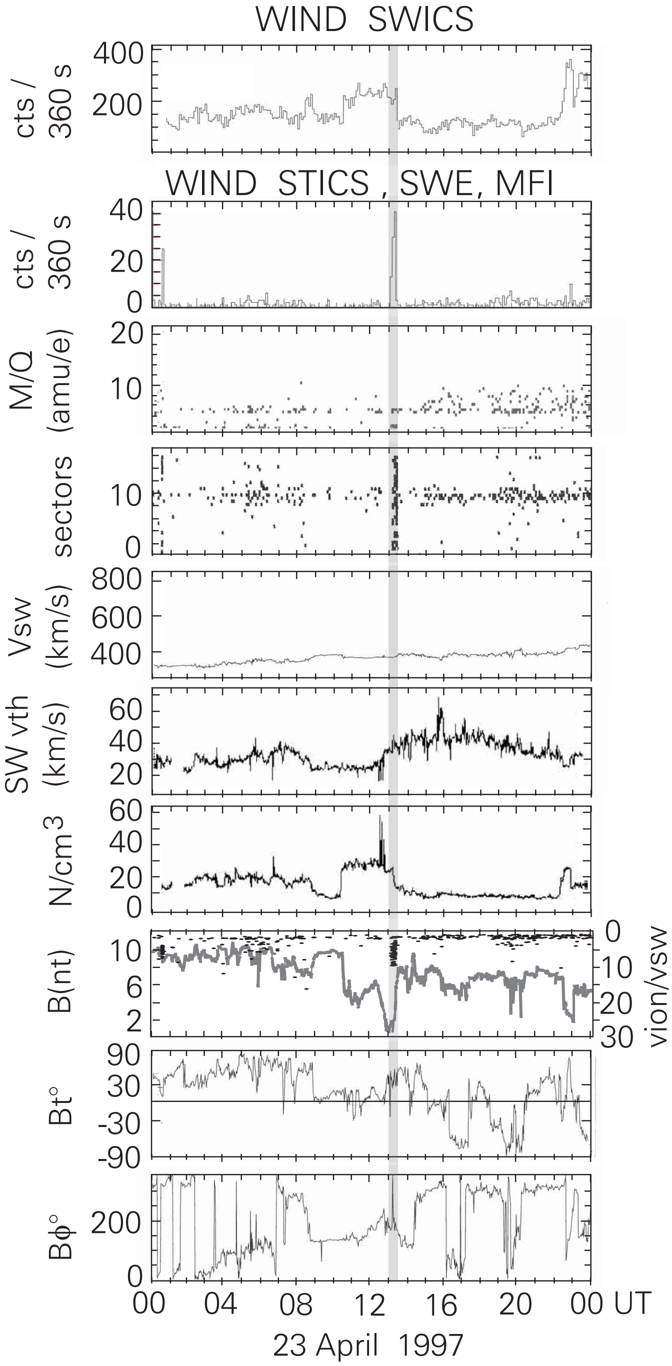

Fig. 4. The same as Fig. 1 for 23 April 1997. Again, two decreases of B appeared at ~10:33 UT and ~13:12 UT. The low energy plasma (E/q = 0.5–31.5 keV/e) started to increase in its intensity during the first B-decrease. Only the second decrease showed suprathermal ions (E/q = 6.5–225 keV/e). Also presented are the thermal velocity and the density of the solar wind plasma. The WIND-S/C was in the libration point L1.

4. Summary of observations

1) The STICS sensor measured numerous particle bursts in the energy/charge range 6.5–225 keV/e near the heliospheric current sheet from 1995–1998. Here only particle bursts were studied which were associated with

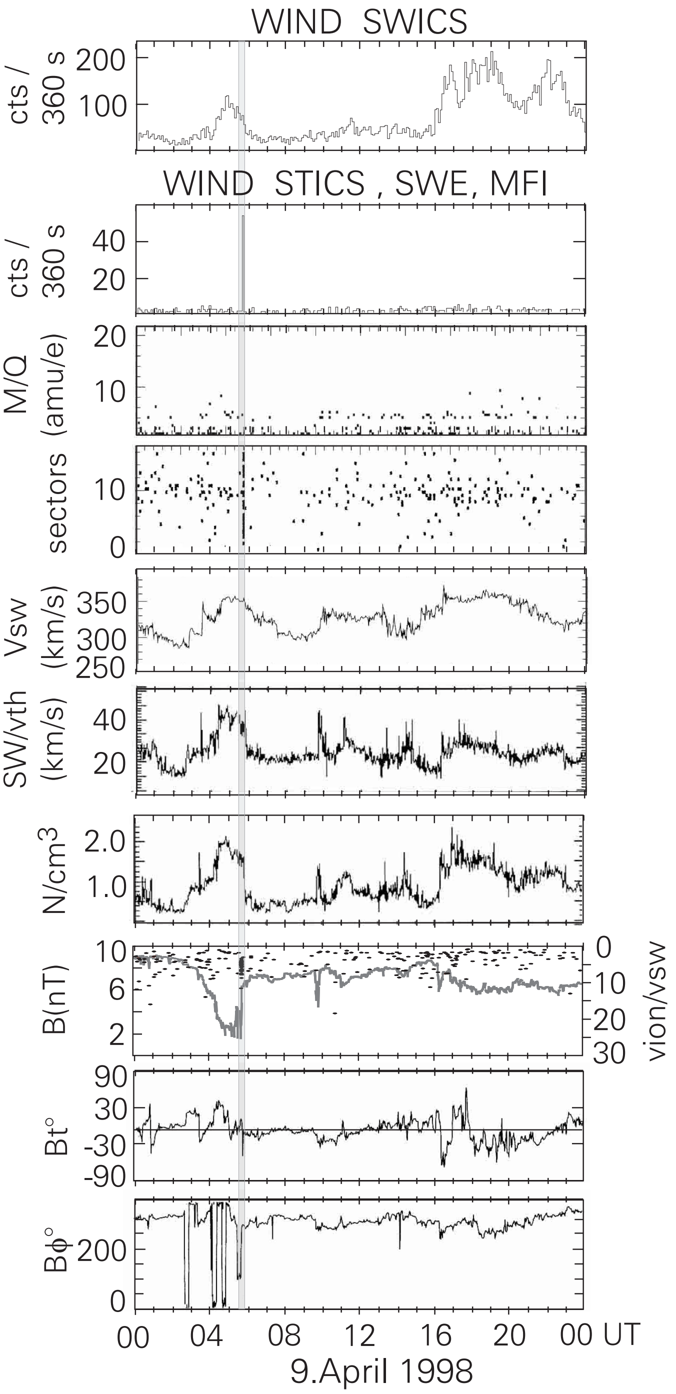

Fig. 5. The same as Fig. 1 for 9 April 1998. The magnetic field depression is associated with increases in the SWICS (E/q = 0.5–31.5 keV/e) ion count rate, a short-lived burst of suprathermal (E/q = 6.5–225 keV/e) ions, as well as increases of the solar wind velocity, its thermal velocity and density. The WIND-S/C was in the libration point L1.

distinct decreases in the magnetic field magnitude and changes in the azimuthal and tangential field direction. The selection criterion was $\Delta B = 2{-}6$ nT, $\Delta B_t \sim \pm 30°$, $\Delta B_\phi \sim \pm 180°$. However, most of the bursts could not be related to characteristic changes of the magnetic field because the WIND/SC was not near the source region.

2) The magnetic field decreases caused increases in the ion density and sometimes also in the ion thermal velocity, the thermal ion count rate 0.5–31.5 keV/e and in the solar wind velocity.
3) At the end of the magnetic field depression, probably in a second acceleration process, short-lived (5–30 min.) bursts of suprathermal particles (6.5–225 keV/e) appear associated with a further short-lived B-decrease or increase and changes in the field direction.
4) The ratio V_{ion}/V_{sw} indicates that the suprathermal particles reach an energy of ~100 keV/e.
5) The sector measurements reveal that the source region can be located sunward or antisunward of the S/C. During isotropic distributions, the S/C was most likely inside the source region.
6) The suprathermal particles consist of protons, α-particles and sometimes $4He^+$ ions.
7) The magnetic field structures convect with the solar wind, as S/C measurements near the libration point L1 and near the Earth have shown.

5. Discussion

The WIND/SC observed during the years 1995–1998 four bursts which are obviously caused by local reconnection processes in the interplanetary magnetic field. The orbit of WIND changed between elliptical orbits around the Earth and halo orbits around the libration point L1. Thus, four bursts in 4 years are caused by the special orbit of WIND. However, many more bursts were recorded in the interplanetary magnetic field, but they could not be related to local reconnection processes because the WIND/SC was far away from the source region.

In Fig. 6 the four bursts are shown once more for proton fluxes (condition mass/charge < 1.5). The proton count rates could then be converted into calibrated energy spectra by using the equation

$$\Delta J/\Delta E \;=\; c/G\; j_1 j_2\; \mathrm{d}E\; \mathrm{d}t\;[\text{protons/cm}^2\text{ s sr keV}] \qquad (1)$$

where

c = count rate/energy step DVS

G = geometric factor = 0.089 cm^2 sr

$j_1 j_2$ = efficiency of the front and back detectors for double coincidences of H^+ ions (see Chotoo 1997, p. 92)

$\mathrm{d}E = 223{-}6.3 \sim 217$ keV

$\mathrm{d}t$ = duration of the bursts = 0.1–0.2 of a day.

The energy of the measured protons is related to the deflection voltage steps DVS of the STICS sensor according to the equation

$$E/Q \;=\; E/Q_o \cdot B_o^{\mathrm{DVS}} \qquad (2)$$

B_o = const = 1.12259.

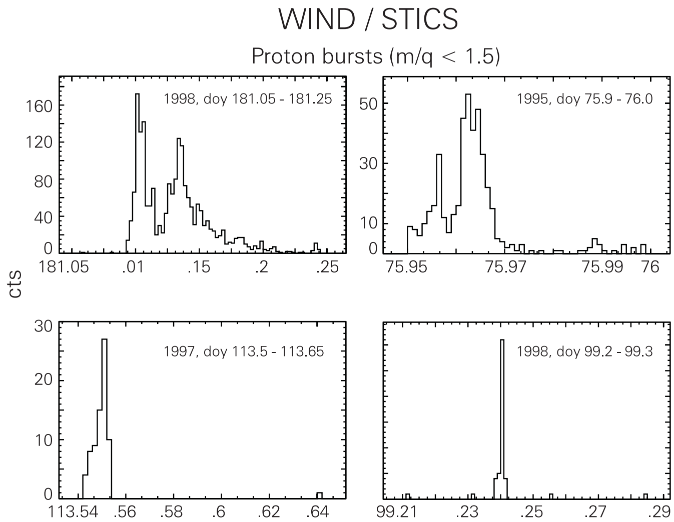

Fig. 6. The four bursts are shown for protons only (mass/charge < 1.5).

The calibrated energy spectra of the 4 bursts are shown in Fig. 7.

The question of whether reconnection processes can occur in the interplanetary magnetic field has been discussed by various authors (Schindler 1972; Bavassano et al. 1976). Turner et al. (1977) considered magnetic holes as a new kinetic scale phenomenon. Some of them result from magnetic merging. McComas et al. (1994) identified the reconnection process ahead of a coronal mass ejection. Winterhalter et al. (2000) described the observed solar wind large-scale magnetic holes as a result of the mirror mode instability, while the plasma was characterized by a high

$$\beta = nkT/(B^2/8\pi). \tag{3}$$

A large fraction of the magnetic holes occurs according to Winterhalter et al. (2000) in interaction regions, in particular near the leading edges of high speed streams. Fränz et al. (2000) found that 78% of the magnetic field depressions are bound by tangential discontinuities and an increased proton temperature anisotropy in the ion plasma. Zurbuchen et al. (2001) studied microscale magnetic holes and claim that they are caused by magnetic reconnection in the high corona beyond the critical point where the solar wind speed equals the local sound speed. The accelerating force produces enhanced density and temperature in the solar wind and a depletion of the magnetic field strength. They conclude that microscale magnetic holes develop in the heliosphere, associated with magnetic reconnection close to the Sun. Neugebauer et al. (2001) studied large magnetic holes in the fast solar wind and found that they are associated with increased density and sometimes increased plasma temperature, and they discussed the various processes that cause the holes. Collier et al. (2001) studied the reconnection process in a magnetic cloud and Chisham et al. (2000) suggested that the mirror mode instability causes magnetic holes. The examples of magnetic field depressions shown in Figs. 1–7 caused thermal and suprathermal particle bursts. As a new result it could be shown that not only the plasma density, solar wind velocity, temperature (or thermal

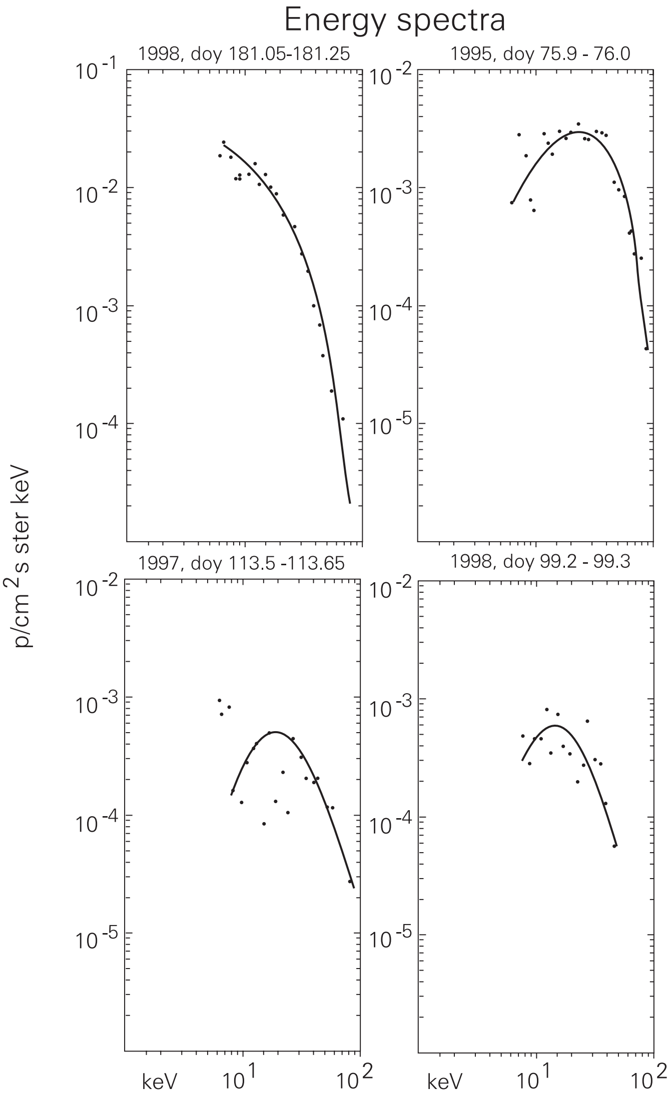

Fig. 7. Calibrated energy spectra of the four proton bursts, averaged over 0.1, 0.15 and 0.2 days, respectively.

velocity), and the SWICS-ion measurements (0.5–31.5 keV/e) can be enhanced during magnetic depressions, but also the count rate of suprathermal ions (6.5–225 keV/e). The relation between plasma temperature and thermal velocity is given by the equation:

$$kT = 1/2\, m\, V_{\mathrm{thermal}}^2. \tag{4}$$

The example depicted in Fig. 5, taken from Zurbuchen et al. (2001) and most of the other examples (Figs. 1–4), show the suprathermal ions at the end of the magnetic field depression. An isotropic distribution of such ions lets us suggest that the WIND-S/C was inside the acceleration region. The ions seem to be trapped in a plasmoid or on closed field lines. Generally, the plasma $\beta = nkT/(B^2/8\pi)$ is also increased, since n and/or T are enhanced, whereas B decreases during the reconnection processes, as shown in Figs. 1–5. We also believe that the reconnection process occurs in the interplanetary magnetic field near the heliospheric current sheet.

The selection criteria for the bursts here presented (strong time correlation between the occurrence of bursts and the decreases in the magnetic field magnitude) allowed us to exclude bursts escaping from the geomagnetic field, solar protons and bursts which could be accelerated in the interplanetary space by CIRs or shocks. We presented strong evidence that reconnection processes in the interplanetary magnetic field, as already found by Bavassano et al. (1976) and McComas et al. (1994) in the topology of the magnetic field, can be associated with proton and α-particle bursts in the proton energy range 6.5 to ~100 keV/e. According to Bavassano et al. (1976), the resistive tearing mode instability is responsible for the reconnection process. The SWICS measurements (E/q = 0.5–31.5 keV/e) demonstrated that often a broader distribution of low energy ions precedes the >6.5 keV/e burst, probably caused by the accelerating force of reconnected field lines (compare Zurbuchen et al. 2001, Fig. 10). The particle energy resulting from the X-line formation process can be calculated using the equation:

$$E = Q \cdot V_A \cdot B \cdot L \tag{5}$$

(see, e.g. Ip & Axford 1986),
where $V_A = B/(4\pi n)^{1/2}$ is the Alfvén velocity
Q = electronic charge
B = magnetic field magnitude
L = length of the neutral line
n = ion density/cm^3.

With typical values for $n \sim 8$ ions/cm^3 and $B = 6$ nT, one finds for the Alfvén velocity $V_A \sim 46.4$ km s^{-1} and for the proton energy ~100 keV when the length of the neutral line $L \sim 250\,000$ km is assumed, which seems not to be unreasonable for the interplanetary space. Fitzenreiter & Burlaga (1978) already found that magnetic holes can have an extension >10^5 km. The particle and magnetic field measurements in the libration point L1 and near the Earth let us conclude that the magnetic field can maintain its shape for ~1 h during which sporadic particle acceleration takes place. Farrugia et al. (2001) described a reconnection event associated with a magnetic cloud which was also observed by WIND on 24 Dec. 1996. They interpreted this observation as MHD discontinuity arriving from a reconnection side closer to the Sun. We analysed the same event according to our method (not shown as figure) and found that the plasma measured by SWICS (0.5–31.5 keV/e) was accelerated, as well as a short-lived burst of 6.5–225 keV/e ions. The maximum velocity reached by the ions was ~9 times the solar wind velocity. The sector measurements of the STICS sensor indicate that the acceleration of the suprathermal ions started most likely somewhat antisunward of the WIND-S/C. The suprathermal ion bursts shown in our Figs. 1–6 and the example described by Farrugia (24 Dec. 1996) are most likely accelerated locally and not close to the Sun, otherwise the 6.5 keV/e and the ~100 keV/e ions should show a distinct velocity dispersion. The travel time of ~100 keV/e and 6.5 keV/e protons over a distance ~1 AU is ~9.5 h and ~37 h, respectively. However, we cannot exclude that near the interplanetary current sheet a still unkown mechanism exists which can also accelerate protons to ~100 keV. Burlaga & Lamaire (1978) predict in their theory of magnetic holes an electric field in z-direction of $Ez \sim 10^{-5}$ V/m at the beginning and at the end of the magnetic field depression. Such an electric field would require an acceleration length of 10^5 V/10^{-5} V/m = 10^7 km which seems to be unrealistically large. Figures 1 and 3, respectively, Figs. 4 and 5 showed that suprathermal bursts appeared at the beginning or at the end of the magnetic field depression. Therefore, we check whether an inductive electric field could be responsible for the particle acceleration. According to

$$-\mathrm{d}B/\mathrm{d}t = \mathrm{curl}\, E, \tag{6}$$

one obtains $-\mathrm{d}B/\mathrm{d}t \sim 7$ nT/600 s $= 0.0117 \times 10^{-9}$ V/m^2 (d$B \sim 7$ nT change in ~600 s time). The dimension of the accelerating region can be estimated from the solar wind velocity $V_{sw} = 375$ km s^{-1} and the duration of 600 s to be ~225 000 km. Assuming a circular area of 225 000 km in diameter, one obtains as an area $F = 3.97 \times 10^{16}$ m^2 for the inductive field and $U = -\mathrm{d}B/\mathrm{d}t \cdot F = 464$ kV. Thus, a particle circulating just a part of this inductive field could gain ~100 keV energy. In conclusion, we consider magnetic field line reconnection and an inductive electric field as the most probable reasons for the described suprathermal bursts.

6. Conclusions

The magnetic field and particle measurements (0.5–31.5 keV/e and 6.5–225 keV/e) of the WIND, ACE and IMP8-S/C in the interplanetary space indicate that reconnection processes in the interplanetary magnetic field can be associated with thermal and suprathermal particles. The maximum particle energies are of the order of ~100 keV/e. Simultaneously obtained solar wind, ion and magnetic field measurements of ACE (located in the libration point L1) and IMP8 (orbiting the Earth in ~30–40 Re distance) reveal that the same magnetic structures and similar particle fluxes appear about 1 hour earlier in the libration point L1 than near the Earth. Inductive electric fields could also be responsible for the particle acceleration.

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