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First identification in energetic particles of characteristic plasma boundaries at Mars and an account of various energetic particle populations close to the planet

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Abstract. Signatures of characteristic boundaries, interpreted to be the bow shock and magnetopause with, between them, the magnetosheath, have been recorded for the first time in energetic particles (<30 keV–>3.2 MeV) in the downstream nightside Martian environment by the SLED instrument aboard *Phobos* 2. Also, energetic particles, interpreted to be oxygen ions, have been recorded by SLED at four distinct locations close to Mars. These include (a) anisotropic fluxes at the terminator shocks with energies of up to at least 72 keV; (b) anisotropic fluxes with energies of up to at least 225 keV inside the magnetopause at a height above the planet of approximately 900 km in the subsolar part of the magnetosphere; (c) fluxes with energies of up to at least 3.2 MeV in the flanks of the magnetosheath displaying quasiperiodic variations (period approximately 45 min) which are synchronous across the recorded energy spectrum and correlated in time with changes in the local magnetic field; (d) beams of oxygen ions with energies of up to at least 55 keV travelling out along open field lines in the magnetotail with, in some cases, a suggestion of confinement close to the neutral sheet. A preliminary discussion is provided concerning the energization of the various populations of particles identified.

Introduction

The *Phobos* 2 spacecraft to Mars and its moons was launched from the Baikonur Cosmodrom on 12 July 1989. *Phobos* 2 had two modes of stabilization, namely three-axis and spin stabilization. In the latter case, the spacecraft rotated about the x-axis (Sun–spacecraft direction) with a period of several minutes. After a cruise phase to Mars of 204 days, *Phobos* 2 was commanded on 1 February 1989 into a series of four highly eccentric orbits about Mars (period approximately 79 h, pericenter approximately 860 km). On 12 February, it was raised to an elliptical orbit of high pericenter (period approximately 86.7 h, pericenter approximately 6407 km), then transferred to perform a series of 112 circular orbits, with period approximately 8 h, at a height above the planet of about 6145 km.

The twin-telescope charged particle detector SLED on the *Phobos* 2 mission utilized semiconductor detectors in two telescopes (Te 1, Te 2) directed, in the ecliptic plane, at 55° to the West of the spacecraft sunline. This line-of-sight direction agrees approximately with the direction of the nominal interplanetary magnetic field at Mars. The geomagnetic factor of each telescope was 0.21 cm^2 sr and the opening angle was, in each case, 40°. The first detector of Te 1 was covered with 15 μg cm^{-2} of aluminium and recorded both ions and electrons. Te 2 was covered with an additional foil which absorbed protons with energies less than 350 keV, but allowed the detection of 35–350 keV electrons.

Particle energies were determined by measuring their energy loss in the solid-state detectors in various energy intervals. The energy channels of Te 1 are listed in Table 1. The instrument did not resolve heavy ions of mass number $A > 4$, although the detectors responded to heavy ions. The energy thresholds of Channels 1–4 of Te 1 for ions of the water group are 55, 72, 225 and 625 keV, respectively. The accumulation time was 230 s. A detailed account of the instrument is contained in McKenna-Lawlor *et al.* (1990).

The only device with particle-detection capability in a related part of the spectrum to be flown near Mars previously had energy thresholds for electrons and protons of 100 keV and 1 MeV, respectively (Vernov *et al.*, 1974).

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Table 1. Energy channels of SLED (p = proton; e = electron; O^+ = oxygen ion; b = background rate)

Ch. 1	34–51 keV	p+e	55–72	keV	O^+
2	51–202 keV	p+e	72–223	keV	O^+
3	202–609 keV	p+e	225–630	keV	O^+
4	0.6–3.2 MeV	p	0.625–3.25	MeV	O^+
5	3.2–4.5 MeV	p	—	—	—
6	>30 MeV	b	—	—	—

The energetic particle events described below, which represent measurements made by SLED in Te 1 while executing circular and elliptical orbits about Mars from 1 February to 26 March 1989, constitute pioneering observations.

Energetic particles at the terminator shocks

In certain circular orbits, particle enhancements in Channel 1 were recorded in association with bow shock crossings at the terminators in SLED Te 1. These events were sometimes associated with minor complementary enhancements in Te 1, Channel 2. No corresponding effects were recorded in the data of Te 2, indicating that ions greater than 350 keV and low-energy electrons were absent.

Figure 1 shows (in panel 3) representative particle data recorded in Te 1, Channel 1, of SLED on 2 March 1989 (Circular Revolution 42) compared (see panels 1 and 2) with the spacecraft–sunline component of the magnetic field B_x and the magnetic field magnitude B, simultaneously measured onboard *Phobos* 2 by MAGMA. (A description of the MAGMA instrument is provided in Aydogar *et al.*, 1989.) At the time of the measurements, the spacecraft was in spin mode and the B_y and B_z components are not shown in the absence of despun data.

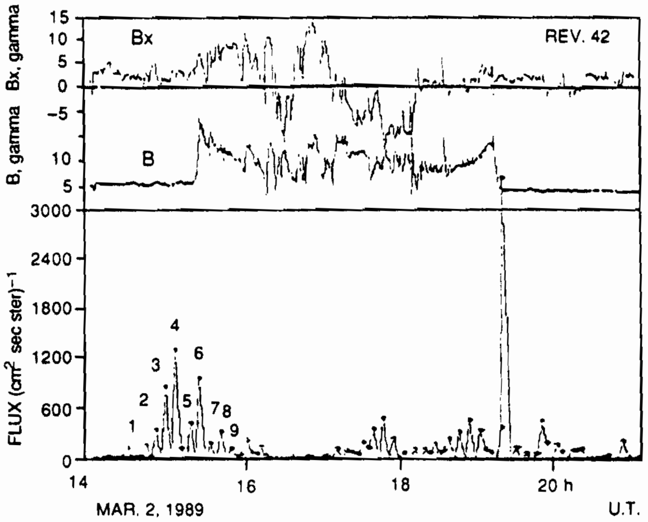


Fig. 1. Panels 1–2 (top) show the Sun–spacecraft line component of the magnetic field B_x and the magnetic field magnitude B measured by the MAGMA instrument from approximately 14:00–21:00 U.T. on 2 March 1989. Panel 3 shows particle fluxes measured by SLED in Te 1, Channel 1

The position of the bow shock, inbound/outbound, is well defined by the abrupt associatively measured increase/decrease in the magnitude of B. It is noted that the spatially associated particle flux enhancements inbound occurred over a broad region spanning bow shock traversal. The amplitudes of the particle increases recorded attained 1–1.5 orders of magnitude, composed in a sequence of relatively wide (1.5 h) peaks, which reduced periodically to the background level. Since the field of view of the SLED aperture was relatively small (40° full cone), this modulation can be interpreted to be due to the spin of the spacecraft and we can infer that the strongly anisotropic fluxes observed constituted a beam of particles. Outbound, a single particle spike was recorded just outside the bow shock (minor typical particle increases, seen in these data to be present deep inside the magnetosphere, are described separately in the next major section).

Figure 1 illustrates just one example from an extensive collection of strongly anisotropic particle enhancements with similar general characteristics associated with terminator bow shock crossings, individually recorded while *Phobos* 2 was executing 112 circular orbits about Mars. During some of these orbits, bow shock associated increases were recorded both inbound and outbound. In other cases, such effects occurred only when the spacecraft was flying either inbound or outbound. In yet other instances, no particle increases at all were recorded in association with crossings of the bow shock. MAGMA data show that the shocks concerned were sometimes parallel, sometimes perpendicular and sometimes intermediate in character. A detailed study is in progress to identify the circumstances (spacecraft orbital characteristics; the background level of disturbances at Mars due to solar activity; etc.) accompanying each kind of record.

Energetic particles inside the magnetopause on the subsolar side

Figure 2 shows data recorded by SLED in Te 1 (Channel 1–6) during orbit 3, together with contemporary magneti data from MAGMA. Following pericenter (05:52 U.T 8 February) and after the spacecraft crossed the mag netopause, the particle fluxes increased significantly, dur ing approximately 26 min, from 05:40 U.T. in Te 1, Chan nels 1–3. The largest enhancement occurred in the lowe energy channel. No special response was recorded in T 2. At this part of the orbit, SLED viewed directly alon the surface of the magnetopause. This was deduced b calculating the pitch angles of the SLED field of vie

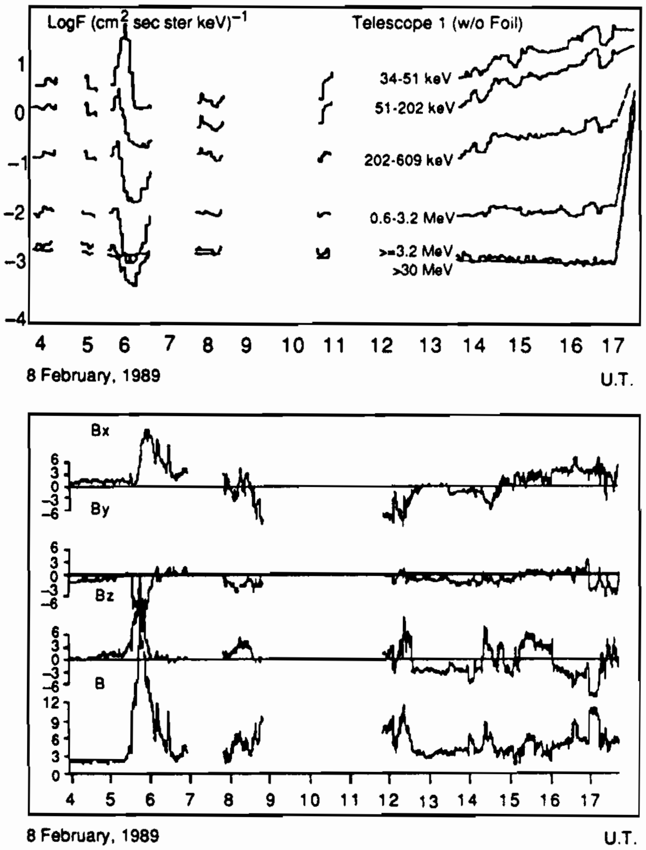


Fig. 2. (Top) Particle fluxes recorded by SLED on *Phobos* 2 in Te 1, Channels 1–6 during elliptical orbit 3 of Mars on 8 February 1989. (There was a gap in these data after 17:15 U.T.) (Bottom) Contemporary magnetic field data recorded by MAGMA onboard *Phobos* 2 (B_x, B_y, B_z, B)

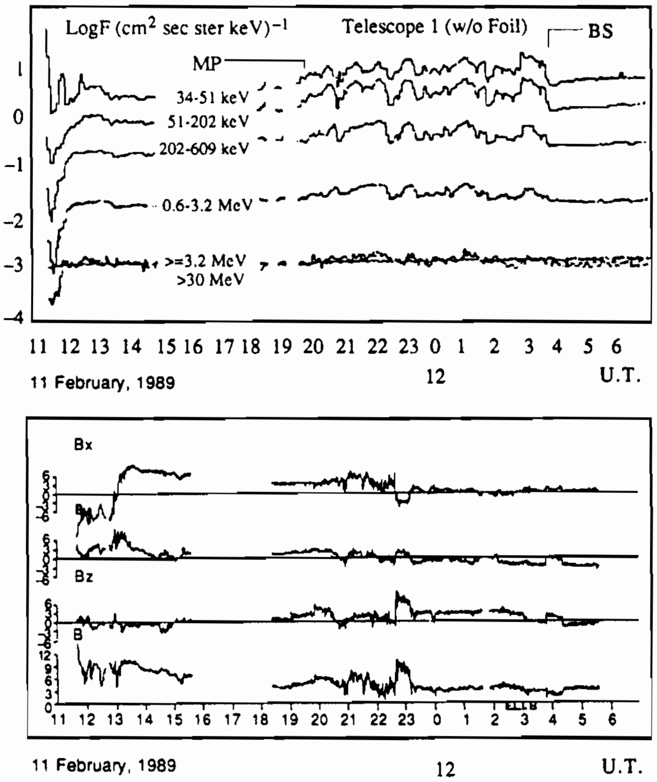


Fig. 3. (Top) Particle fluxes recorded by SLED on *Phobos* 2 in Te 1, Channels 1–6 during elliptical orbit 4 of Mars on 11–12 February 1989. The locations of the distant bow shock and magnetopause crossings are indicated by the letters BS and MP, respectively. (Bottom) Contemporary magnetic field data recorded by MAGMA onboard *Phobos* 2 (B_x, B_y, B_z, B)

(FOV) relative to the magnetic field vector measured simultaneously by MAGMA and confirming that the local magnetic field vector was inside the SLED FOV while the maximum was measured. The effect was followed by a depression in the particle fluxes of about one order of magnitude. The latter decreases, which are particularly clearly seen in Fig. 2 in the data of Te 1, Channels 3–5, were due to magnetic shadowing (Afonin *et al.*, 1989) (magnetic shadowing would occur at locations in the orbit where the instrument sights in the interplanetary field direction, but the field of view is occulted by the planet body: analysis of simultaneous measurements of the present magnetic and particle data has shown that the depressions in counts, mentioned above, occurred at exactly such orbital locations).

In orbit 4 there was a telemetry gap close to pericenter (at 11:30 U.T.) but, as shown in Fig. 3, from about 4 min thereafter, the declining phase of a flux enhancement was visible in the data of Te 1, Channels 1–3 as, again, SLED viewed along the boundary of the magnetopause at this part of the orbit. Te 2 showed no associated flux enhancements. Contemporary magnetic data from MAGMA are provided for comparison with the particle records.

It is noted that accelerated particles were also recorded by SLED at the same general location during orbit 2 (not illustrated), so that the effect endured over at least an 8 day period. During orbit 1, the ambient conditions were profoundly disturbed by solar activity when the spacecraft was at an equivalent location.

Energetic particles in the magnetosheath

During each of the four elliptical orbits of the planet, *Phobos* crossed the distant bowshock of Mars at $X \sim 15$ R_M. At the time of the first such orbit (1 February), the environment of the planet was disturbed by the presence of particles of solar origin during this crossing, and these data are not considered here. The SLED instrument was switched off, due to spacecraft manoeuvres, during the distant bow shock crossing executed in orbit 2, as well as at various times along extensive lengths of the trajectories of orbits 3 and 4.

In Fig. 2, following several data gaps, fluxes showing synchronous variations in the first four energy channels of Te 1 are seen to be present from approximately 14:00 U.T. while SLED was traversing the magnetosheath. These variations, which were quasiperiodic with a period of approximately 45 min, were superimposed on a generally increasing rise in the flux level recorded in each channel. Significant jumps (down/up) occurred at 16:50 and at 17:15 U.T., respectively. After this time there was a gap in the energetic particle data. Magnetic data recorded by the *Phobos* 2 magnetometer MAGMA indicate the occurrence of a bow shock crossing (not illustrated) at approximately 19:00 U.T.

During orbit 4 (see Fig. 3), the instrument was switched off for approximately 3 h after 15:00 U.T. Smooth fluxes were recorded thereafter from approximately 18:30 U.T. Thereafter, SLED recorded certain characteristic boundaries in the distant Martian magnetotail. At approximately 19:45 U.T. (designated by the letters MP on the figure) the observations are interpreted to indicate that *Phobos* 2 crossed the magnetopause and entered the magnetosheath. As in the previous orbit, close synchronism is displayed between quasiperiodic flux variations (approximate period $T = 45$ min), recorded in the first four energy channels ($> \sim 30$ keV–3.2 MeV). Some temporally related minor enhancements are also visible in the data of Channel 5 (>3.2 MeV). A sharp simultaneous drop in the fluxes in all channels occurred at approximately 03:45 U.T. on 12 February as the spacecraft crossed the bow shock (marked BS) and entered the undisturbed solar wind.

Events in the deep magnetotail

Figure 4 presents, on a linear scale, the intensities of energetic particle fluxes recorded in Te 1, Channel 1 of SLED during a succession of circular orbits (20–50) around Mars. Each record is, for clarity of presentation, given a small relative vertical shift. Gaps represent periods when the instrument was switched off during spacecraft manoeuvres. Events having intensities less than a particular threshold are suppressed in this presentation. No complementary events were observed in Te 1, Channel 2 or in the data of Te 2.

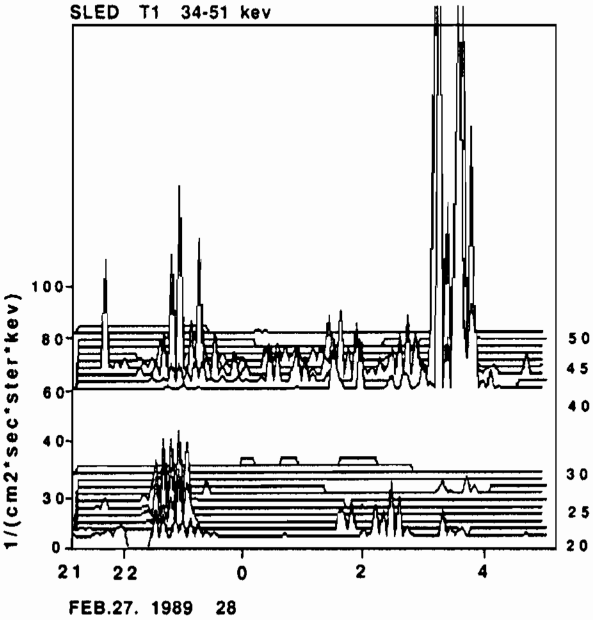


Fig. 4. The intensities, on a linear scale, of energetic particle fluxes recorded in Te 1, Channel 1 of SLED during a succession of circular orbits (20–50) around Mars. Each record is, for clarity of presentation, given a small relative vertical shift. The time of the first orbit only is shown. Some data are missing due to the switching off of SLED during spacecraft manoeuvres

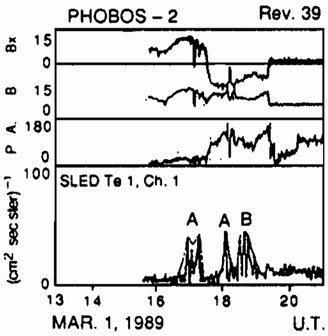
The composite records show clearly that at least two categories of particle activity were recorded by SLED while in circular orbit, namely large enhancements associated with bow shock crossings (as described in the previous major section), and less intense, but nevertheless well-defined, events occurring while the spacecraft was deep in the magnetotail.

Comparisons between the particle records and contemporaneous magnetic field data from MAGMA were made for all 112 circular orbits of Mars executed by *Phobos* 2. Due to various circumstances (including breaks in the particle records when SLED was switched off during spacecraft manoeuvres; the absence of simultaneous magnetic field observations; disturbed interplanetary conditions accompanying, in particular, solar flaring associated with energetic particle emissions from 6 to 26 March 1990), the data from only 13 circular orbits were finally found to be suitable for detailed analysis.

Minor particle flux enhancements recorded deep in the magnetotail during the 13 circular orbits mentioned have been subdivided into two classes, namely those with pitch angles within $\pm 40°$ of $0°$ and $180°$, and those within $\pm 40°$ of $90°$. Those events with pitch angles close to $0°$ or $180°$ are described as field-aligned or Class A events, and those with pitch angles close to $90°$ are described as events of Class B.

Figure 5 (bottom panel) shows particle fluxes recorded by SLED in Te 1, Channel 1 on 1 March 1989 (revolution 39) during relatively quiet interplanetary conditions. Panel 1 (top) and panel 2 show, respectively, the Sun–spacecraft component of the magnetic field B_x and the absolute value of the magnetic field recorded simultaneously by the *Phobos* 2 magnetometer (MAGMA). The characteristic decrease in B_x shown in panel 1 before 18:00 U.T. marks the transition of the spacecraft from one lobe of the magnetotail to the other. The exit bow shock crossing was at approximately 19:40 U.T. Panel 3 shows how the pitch angles of the central axis of the SLED field of view, calculated from the measured magnetic field values, varied with time.

As seen in Fig. 5, panel 4, three well-defined particle



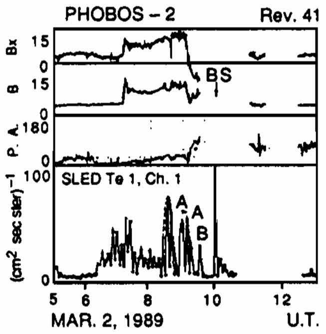


Fig. 5. (Left) For circular revolution 39, 1 March 1989, 13:30–20:30 U.T.; panels 1–2 (top): Sun–spacecraft component of the magnetic field B_x and absolute value of the magnetic field; panel 3: pitch angle of the central axis of the SLED FOV calculated from the magnetic field measurements; panel 4: particle counts in SLED Te 1, Channel 1. For the meaning of the letters A and B see the text

Fig. 6. (Right) As for Fig. 5, but for circular revolution 41, 2 March 1989, 05:30–12:30 U.T.

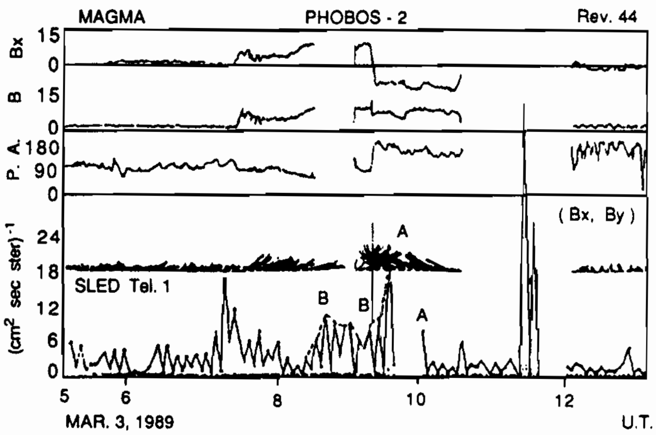


Fig. 7. Panels 1–3 as in Fig. 6 but for circular revolution 44, 3 March 1989, 05:30–13:00 U.T.; panel 4: representation of the magnetic field vectors (B_x, B_y) along the trajectory of *Phobos* 2; panel 5: particle counts in SLED Te 1, Channel 1

enhancements were recorded in Te 1, Channel 1 during the approximately 4 h traversal by *Phobos* 2 of the magnetotail during circular revolution 39. The first particle enhancement (Class A) was recorded in the first lobe traversed and the second, also of Class A, was in the second lobe. The third event (Class B) occurred deeper into the magnetotail. Modulation of the records due to spacecraft spin is, in each case, clearly evident. The increased fluxes recorded were evidently strongly directed. Figure 6, bottom panel, shows other examples of events of Classes A and B recorded by SLED during circular revolution 41.

In our selected sample of 13 circular orbits, 14 examples of events of Class A and 7 examples of events of Class B were identified. Two events were recorded in the overall sample which were characterized by a rapid, then sustained, change in pitch angle which resulted in a particular enhancement passing through an intermediate state from one of our two categories to the other. An example, recorded during revolution 44, is shown in Fig. 7 which illustrates the case of an event of Class B changing over to being one of Class A. This changeover occurred, as shown by the B_x record in the top panel, at the time when the spacecraft transited from one tail lobe to the other. The vector plot of (B_x, B_y) shown in panel 4 illustrates the fast change of magnetic field direction characterizing this transition. The second example (not illustrated), which was recorded during revolution 42, also occurred very close to the neutral sheet.

Discussion

Bow shock accelerated particles

Particle bow shock acceleration is already a well-known effect in association with the Earth's bow shock and with various interplanetary shocks. Usually two bow shock acceleration mechanisms are invoked to explain such observations, namely diffuse acceleration, which is most effective for quasilongitudinal or longitudinal shocks (with $\theta_{nB} = 0°$–$45°$), and drift acceleration, which is most effective for quasiperpendicular or perpendicular shocks (with $\theta_{nB} = 45°$–$90°$), where θ_{nB} is the angle between the shock normal and the mean upstream magnetic field.

As pointed out by Ip (1990), diffuse bow shock acceleration is limited by the dimensions of the system concerned and, since the Martian bow shock is much smaller than that of the Earth, it is reasonable to infer that the diffuse acceleration of ions would not lead to high energies at this planet.

Shock drift acceleration of ions originating upstream of the bow shock can occur according to a process whereby a particle gains energy by drifting in the inhomogeneous magnetic field at the shock front in a direction parallel to the $\mathbf{v} \times \mathbf{B}$ electric field (where $\mathbf{v}$ is the plasma bulk velocity and $\mathbf{B}$ is the magnetic field). The amount of energization produced depends on the number of times the particle crosses the shock and, in this connection, some authors combine the shock drift mechanism with Fermi first-order acceleration to demonstrate that a particle can encounter the shock several times. As shown by Decker (1983), shock spike events can be produced by the single-encounter shock drift acceleration of a charged particle at a quasi-perpendicular shock, and the existence of a high-intensity spike in close temporal association with such a shock (such as that illustrated in the case of the present data set in Fig. 1), can then be explained as due to the kinematic accumulation of particles accelerated and transmitted downstream of the shock. A comparison of SLED data with MAGMA measurements obtained before and after the terminator bow shock crossings executed by *Phobos* during almost all of the circular orbits of the planet (including orbit 42) indicates that, in this sample, shock spike events were always associated with quasiperpendicular shocks.

For high-speed (500–700 km s^{-1}) solar wind conditions, such as were measured at Mars in February–March 1989 by the TAUS experiment onboard *Phobos* 2, the electric field E can be estimated (taking a conservative value for the magnetic field of $B = 6$ nT) to lie at least in the range 2.4–3.5 mV m^{-1}. Assuming for the Martian bowshock a diameter of $5R_M = 16{,}965$ km and taking an effective acceleration length of 10,000 km, energy gains of $E = 24$–35 keV and 48–70 keV are then attainable by O^+ and O^{2+} ions, respectively. This mechanism would be sufficient to explain the accelerated ions recorded by SLED in Te 1, Channels 1–2 in association with the Martian (terminator) shocks. A sufficient population of seed neutral oxygen atoms to provide the observed flux increases at a height above Mars of 6000 km is provided, under favourable magnetic field conditions, by hot atmospheric oxygen ions produced in the dissociative recombination of O_2^+ ions [see estimations by Afonin *et al.*, 1991, which yield a value for n(O) of approximately 10 cm^{-3} at the height above the planet of the *Phobos* 2 circular orbit].

Ions at the subsolar side

Flux enhancements were recorded in the same general location in the close environment of Mars over 8 days at

$\sim$900 km altitude during three elliptical orbits of the planet. These enhancements were located inside the magnetopause on the subsolar side. Several possible explanations to account for these enhancements were suggested by Afonin *et al.* (1989) when they were first identified. The then-suggested possibility that sunlight reflected from the body of Mars might have produced the observed signatures can now, through analysis of the relevant orbital dynamics, be discounted. An attractive mechanism to account for the observations is the adiabatic acceleration of suprathermal particles to keV energies which could occur in the relevant environment close to the planet where the magnetic field lines display a pronounced compression.

The following magnetic field increases were recorded at the relevant location by the MAGMA experimenters: orbit 1, 10 G; orbit 2, 6 G; orbit 3, 10 G (orbit 4; not available). If we assume that all of the ion energy E was in E_{perp}, then we can expect about an order of magnitude increase in the particle flux, since the increase in perpendicular energy is proportional to the local magnetic field increase due to the "piling-up" effect. A seed population of suprathermal particles with energies $E > 30$ keV would, within the framework of this mechanism, be required to produce the observed enhancement. In the quiet solar wind, particles of such energies would not be sufficiently abundant to produce the recorded effect. Further, the SLED field of view, which was only $\pm 20^\circ$, was directed along the local magnetic field during the flux enhancements so that the instrument could not observe particles with large pitch angles (an increase of perpendicular energy leads to an increase in pitch angle). An increase in local particle density due to the piling-up effect could, however, explain our observation, as the increase in the observed particle flux is approximately as great as the recorded increase in the ambient magnetic field. Further careful analysis and modelling of the data is required to elucidate the situation, however, since the gyroradii of protons with energies of several tens of keV are of the order of tens of thousands of kilometres, while our observations were made at a height of less than 1000 km above Mars. This kind of analysis/modelling is planned at present.

Magnetosheath particles

Table 2 shows the maximum energies attainable by several ions at the solar wind speeds pertaining at Mars in February–March 1989 (500–700 km s^{-1}, recorded by the TAUS observers) as a result of the pickup process (using the well-known expression $E_{max} = 2M v^2 \sin^2 \alpha$; where M represents ion mass, v the solar wind velocity and α is the angle between the solar wind and the interplanetary magnetic field direction). It is highly likely that the particles recorded in the magnetosheath represent ions of the water group since (see also Tables 1 and 2) protons accelerated by the pickup process would be below the threshold recorded by the SLED detectors. However, the appearance of such particle enhancements in Te 1, Channels 1–5 clearly cannot be explained by the pickup process acting alone.

Table 2. Energy of pickup ions

Velocity (km s^{-1})	H^+ (keV)	O^+ (keV)	O_2^+ (keV)	CO_2^+ (keV)
500	5.25	100	200	275
700	12.25	196	392	539

The interaction of the Martian magnetosphere with the interplanetary magnetized medium could possibly lead to a local and sporadic merging of planetary and interplanetary magnetic field lines at the dayside of the planet resulting, like at the Earth, in the acceleration of charged particles which could then propagate along the magnetosheath boundary from the day to the nightside, as already observed in the case of the Earth's magnetosphere (see Gosling *et al.*, 1986 and Paschmann *et al.*, 1986, among others).

Characteristic boundaries of the distant Martian magnetotail, recorded in energetic particle data during elliptical orbits 3 and 4, are identified to be the magnetopause and the bow shock with, between them, a broad region representing what is called the magnetosheath at the Earth. The authors are not aware that any other instrument aboard the spacecraft has hitherto defined these features definitely and it is the first time that such boundaries have been identified in energetic particles (<30 keV–>3.2 MeV).

The quasiperiodic variations ($T \sim 45$ min) of energetic particles, recorded in the flanks of the magnetosheath, are not explained at present. Those variations recorded during orbits 3 and 4 show some correlation with variations in the local magnetic field recorded, simultaneously, by the MAGMA instrument. An in-depth theoretical study of the available records is presently in progress.

Energetic particles in the deep magnetotail

In considering plausible acceleration possibilities for the Class A particle enhancements, it is noted that the source of the observed energetic ions might have originated in the pickup process on the dayside of the planet. In this connection, Table 3 shows the range of variation of the angles of elevation and azimuth of the interplanetary magnetic field in the undisturbed solar wind 1 h before and 1 h after inbound/outbound bow shock crossings during representative orbits 39, 41, 42 and 44. In general, these data show that the pertaining conditions were not very favourable for permitting dayside pickup ions to be recorded by SLED deep in the magnetotail. The situation during orbit 42 was particularly unfavourable. However, the successful arrival of such ions at SLED cannot be excluded and detailed modelling pertaining to the prevailing conditions when Class A and Class B events were recorded is now required.

With regard to the identity of the particles recorded in the deep magnetotail, protons of 34–51 keV and O^+ ions of 55–72 keV could each have stimulated Channel 1 (see Table 1). However, Lundin *et al.* (1990) have already

Table 3. Variations in the angles of azimuth and elevation of the interplanetary magnetic field 1 h before and 1 h after Martian bow shock crossings (inbound and outbound)

Revolution	Range of variation 1 h before bow shock crossing (inbound)		Range of variation 1 h after bow shock crossing (outbound)	
39	Data gap		Azimuth	40 –60
			Elevation	50 –80
41	Azimuth	300°–320°	Data gap	
	Elevation	0°–20°		
42	Azimuth	20°–60°	Azimuth	20 –0
	Elevation	0°–80°	Elevation	40 –60
44	Azimuth	20°–60°	Data gap	
	Elevation	50°–30°		

reported the presence of O^+ beams with energies up to several keV in the central tail and it is very probable that the signatures recorded by SLED were also produced by O^+ ions. It is suggested that such ion beams travelling planetwards along flux tubes in the Martian magnetosphere might produce auroral effects similar to those occurring in the magnetosphere of the Earth, while ions travelling outwards could escape along open field lines. Such oppositely travelling particles could originate in reconnection events similar to those already reported by Sarris *et al.* (1976) to be present in the geomagnetic tail.

It is interesting to speculate if the Class B events might have represented confined particles but, at the present time, not enough is known about the configuration of the Martian magnetic field to support such an interpretation. However, during the orbits investigated, the magnetic field intensity at the times of the Class B events was in the range 10–20 γ and in no case was it less than 10 γ. Protons with energies of 30 keV and $B = 10\ \gamma$ have gyroradii of about 2500 km. Thus, if we consider that the radius of curvature of a closed field line should be of the order of 2–3 times this value in order to at least partially confine particles, then their location of observation at approximately 9000 km from the planet is not unreasonable.

Fast transitions from one category of enhancement to another close to the neutral sheet could represent the sampling by SLED of different particle populations in the individual tail lobes traversed. The fact that enhancements of Classes A, B and A/B were not recorded during every orbit could either reflect changes with time in the spacecraft trajectory (R varied over the orbits considered between 9300 and 9730 km) and/or may be due to dynamic changes within the tail itself.

Conclusion

SLED has recorded, in energetic particles (<30 keV–>3.2 MeV), certain characteristic boundaries of the downstream nightside Martian environment. These we identify to be the bow shock and the magnetopause, with a broad region between them characterized by synchronous quasiperiodic ($T \sim 45$ min) variations across the recorded energy spectrum which we deem to be what is called the magnetosheath at the Earth. The authors are not aware that any other instrument aboard the spacecraft has hitherto defined these regimes definitely.

The SLED observation of energetic particles in the Martian magnetotail is unexpected. As reported by Yeroshenko *et al.* (1990), MAGMA observations in the distant Mars tail indicate that it is composed of draped interplanetary flux tubes, as opposed to field lines rooted in the planet. Such induced, or cometary-type tails are not generally expected to accumulate free energy from the solar wind and later release it through reconnection, as does the intrinsic field of the Earth [see arguments re the Venus tail of Saunders *et al.* (1986) and Slavin *et al.* (1989); re the P/Giacobini–Zinner tail of Slavin *et al.* (1986a, b); contrary arguments are, however, given by Russell (1986) and by Axford (1991), among others].

Energetic particles, interpreted to be of the water group, are demonstrated (using *in situ* SLED measurements) to be present at four distinct locations in the close Martian environment. These include (a) anisotropic beams at the terminator shocks with energies of up to at least 72 keV; (b) particles with energies of up to 225 keV inside the magnetopause and adjacent to it at the subsolar side; (c) particles with energies of up to at least 3.2 MeV in the flanks of the magnetosheath, showing magnetic-field-related quasiperiodic variations ($T \sim 45$ min); (d) beams of oxygen ions with energies up to at least 55 keV travelling out along open field lines in the magnetotail, with (in some cases) a suggestion of confinement close to the neutral sheet.

The SLED observations of a population of heavy pickup ions in the plasma sheet separating the lobes of the tail are consistent not only with the ASPERA/*Phobos* results of Lundin *et al.* (1990), but also with the TAUS/*Phobos* observations of Verigin *et al.* (1991) and the PVO distant tail measurements made at Venus by Slavin *et al.* (1989).

An in-depth analysis of SLED data and of simultaneously acquired MAGMA data is now required in order to form more detailed conclusions concerning the several energetic particle populations identified in the Martian environment. Theoretical efforts are also necessary to establish the mechanism of their energization.

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