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An overview of energetic particles (from 55 keV to >30 MeV) recorded in the close Martian environment, and their energization in local and external processes

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Abstract. Observations made by the SLED particle detector on Phobos-2 in the close Martian environment from 29 January to 27 March, 1989 during the early rising phase of Solar Cycle 22, show the frequent presence close to the planet, under reasonably "quiet" interplanetary conditions, of particles with energies (E) in the range from several tens of, to several hundred, keV. Under disturbed interplanetary circumstances, particles reaching energies of several tens of MeV were recorded close to Mars.

Those particles in the keV range were observed at well-defined locations, i.e. at the Terminator Shocks (E up to ≈ 600 keV); just inside the subsolar Planetopause (E up to ≈ 225 keV), and travelling down the Tail, $E \geq 55$ keV. These three populations are herein suggested, instancing various candidate mechanisms, to have been energized by processes local to the planet. Since the seed particles for ions accelerated at the Terminator Shocks may comprise ambient, pre-accelerated, solar particles, the energies of ions detected by SLED during Bow Shock transits was observed (during two months) to vary between ≈ 50 keV and ≈ 600 keV.

Particles with energies up to several tens of MeV which were found to suffuse the close planetary environment over extended periods, are interpreted to have been produced in association with solar processes external to Mars (Co-rotating Interaction Regions; Gradual and Impulsive Solar Events).

Particle enhancements in the keV range recorded by SLED (under favourable magnetic conditions) during Bow Shock traversals, provide topographical information concerning the location of the Martian subsolar and distant shock surfaces. These observations constitute a new data set, complementary to those determinations of key boundaries derived from plasma and magnetic field measurements made aboard various American and Russian spacecraft at Mars which, for more than thirty years now, have been generally used in modelling the Solar Wind interaction with the planet. Three-dimensional measurements made at low altitudes over long dwell times are presently required to provide further insights into those local processes whereby populations of keV particles discovered in SLED data, close to the inbound Planetopause and travelling down the Tail, are individually energized. © 1998 Elsevier Science Ltd. All rights reserved

Introduction

The presence of a Bow Shock upstream of Mars was first established using instrumentation carried aboard the Mariner-4 spacecraft in 1965, and the Mars 2, 3 and 5 orbiters in 1971 and 1972, (Smith, 1969; Dolginov *et al.*, 1976; Gringauz *et al.*, 1976; Vaisberg *et al.*, 1976 and Gringauz, 1981). Mariner-4 passed within 9700 km of Mars. The Mars 2, 3 and 5 orbiters, between them, approached no nearer to the planet than 1100 km.

In 1989, *in situ* studies of the Martian Bow Shock were made using various particles and fields experiments carried aboard the Phobos-2 Mission, see for example Grard *et al.*, 1989a, 1989b; Lundin *et al.*, 1989; Riedler *et al.*,

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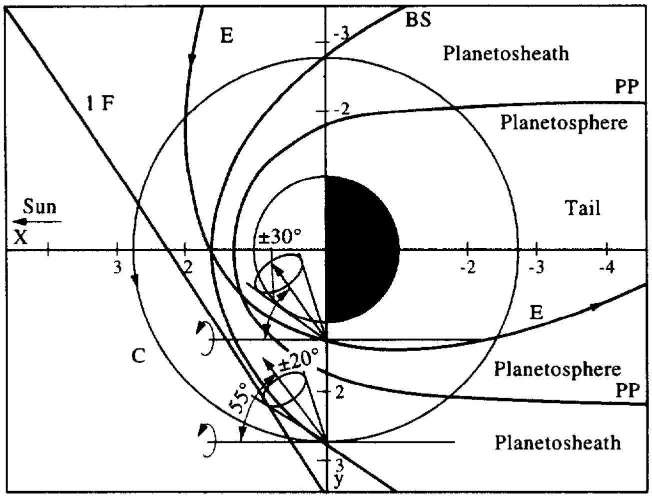

Fig. 1. The encounter of Phobos-2 with Mars, showing part of an elliptical orbit (E) and a circular orbit (C). Also shown are the Bow Shock (BS), The Planetosheath, The Planetopause (PP), the Planetosphere/Tail and the nominal Interplanetary Magnetic Field (IF). The line of sight direction of SLED when in E and C is indicated in each case

1989 and Rosenbauer *et al.*, 1989a. This spacecraft, from 29 January, 1989 executed four elliptical orbits around Mars with periapsis and apoapsis altitudes of approximately 850 km and 80 000 km respectively. In Fig. 1, a representative elliptical orbit (labelled E) is shown relative to the general positions of important plasma boundaries (BS/Bow Shock; PP/Planetopause) and regimes (Planetosheath; Planetosphere/Tail) traversed by the spacecraft, based on plasma and magnetic field measurements (see below).

On 12 February, the elliptical orbit of the spacecraft was corrected so that its percentre came closer to the orbit of the Phobos Moon. In turn, on 18 February, this "transition orbit" was circularized at an altitude a little above that of Phobos (planetocentric distance $2.84R_M$). In Fig. 1, a representative circular orbit is labelled C. The spacecraft was next transferred to a "quasi-synchronous" orbit on 21 March (such that it orbited around Mars practically in synchronism with Phobos). Thereafter, on 27 March in the course of various manoeuvres to approach closer to the Phobos Moon, radio contact with the spacecraft was lost, Sagdeev and Zakharov, 1989.

The Phobos-2 payload featured a suite of experiments dedicated to plasma studies. Among these instruments, magnetic fields were measured using two, triaxial, fluxgate magnetometers named MAGMA (Magnetic Field Near Mars) and FGMM (Flux Gate Magnetometer Mars) respectively, Riedler *et al.*, 1989. Information concerning plasma waves was provided by the PWS (Plasma Wave System) experiment. PWS had the capability to measure electric fields from d.c. up to 150 kHz. It also measured the plasma density distribution using a Langmuir probe and monitored the potential of the spacecraft with respect to one of the spherical probes which formed the electric antenna (Grard *et al.*, 1989a).

The three-dimensional plasma composition experiment ASPERA (Automatic Space Plasma Experiment with a Rotating Analyser) provided compositional information, as well as the energies and angular distributions of (a) ions with energies 0.5 eV/e–24 keV/e and (b) electrons with energies 1 eV–50 keV at Mars (Lundin *et al.*, 1989). The TAUS (Torroidal Analyser Spectrometer) instrument measured the energy per charge and angular spectra of the three species of ion (H^+, He^{2+} and heavy ions covering the mass per charge range from 3 to œ), Rosenbauer *et al.*, 1989a, 1989b; Verigin *et al.*, 1991.

As seen in the record secured by the PWS experiment, the Martian Bow Shock crossings were characterized, close to the shock ramp detected in magnetometer data, by an abrupt decrease in spacecraft potential; by a peak in the electric field intensity recorded in the middle frequency range (100 Hz to 6 kHz), and by a characteristic change in the electric field spectrum. A drop in spacecraft potential observed when the spacecraft exited the Solar Wind and entered the Planetosheath region reflects an associated increase in ambient electron flux (Trotignon *et al.*, 1991a, 1991b, 1993).

There has been considerable discussion in the literature concerning the terminology that should be applied to a well-defined plasma boundary identified between the Bow Shock and the Martian atmosphere. In this connection, the appellations Planetopause, Magnetopause, Aeromagnetopause and Ion Composition Boundary were variously applied by different experiments when describing related signatures recorded by their individual instruments. A careful study of these reports by Trotignon *et al.*, 1996 indicates that all of the above-mentioned boundaries can be shown to correspond with a plasma transition region identified in data of the PWS. The latter boundary was assigned the name "Planetopause" by the PWS experimenters. At this transition, in PWS data, the spacecraft potential exhibited a decrease, indicating an enhancement in plasma pressure in the Planetopause Boundary layer (Grard *et al.*, 1991, 1993). In addition, a peak in the electric field level was recorded in the frequency range from nearly d.c. up to 6 Hz, while the level of plasma turbulence in the Planetosheath decreased regularly from the shock front-reaching a minimum in front of the Planetopause Boundary and reappearing again, suddenly, at a much higher intensity, just behind it. Characteristic Planetopause signatures were, in addition, recorded in PWS data in the frequency range 0.1–50 Hz; in the middle frequency range (100 Hz–6 kHz) and in the lowest frequency filter (0.2–10 Hz), see Trotignon *et al.*, 1996.

The ASPERA Team recognized in their Phobos-2 data, beyond the inbound Bow Shock, a plasma boundary which they called the Magnetopause (adopting a terminology traditionally used by investigators of the terrestrial Magnetosphere that recognizes the presence of the geomagnetic field). See also Gringauz, 1976. This feature was described as presenting a boundary such that, on one side (within the "Magnetosphere") O^+ ions of ionospheric origin prevailed while, on the other side (within the "Magnetosheath") Solar Wind protons were predominant. This interface was deemed by Trotignon *et al.*, 1996 to correspond with the Planetopause identified (see above) in the PWS measurements. The ASPERA Team also identified a feature within the plasma which they called the Mass Loading Boundary (MLB). This was defined to comprise a frontier between that region where the shocked Solar Wind plasma dominates and the regime inside which planetary particles significantly affect the Solar Wind flow (Lundin *et al.*, 1990, 1991, 1993; Lundin and Dubinin, 1992).

Using the same set of experimental measurements from Mariner-4 and Mars 2, 3 and 5, some authors concluded that Mars has an intrinsic magnetic field (disagreeing with each other only with respect to some details), while others concluded that Mars has no intrinsic magnetic field. In an overview of these findings, Slavin *et al.*, 1991 concluded that Mars either presents "a hybrid, weak, intrinsic magnetic field/ionosphere obstacle to the Solar Wind" (as argued for example by Dolginov, 1976; Bauer and Hartle, 1973 and Slavin and Holzer, 1982), or exhibits "a purely ionospheric interaction" (as deduced for example, by Vaisberg, 1976; Cloutier and Daniell, 1979; Russell, 1979 and Luhmann *et al.*, 1987). The addition of Phobos-2 observations to the above mentioned data set was shown by Slavin *et al.*, 1991 to add some weight to the evidence for the existence at Mars of a modest ($\approx 10^{22}$ G cm^3) intrinsic magnetic field. However, certain remaining interpretational problems were deemed by these authors to require further (and as yet unavailable) *in situ* measurements before the question can be fully resolved.

For the present text it was decided to use the prefix "planeto" when referring to regions and interfaces which differentiate various plasma regimes around Mars. This convention, which follows that of Grard *et al.* (1991), was earlier justified by these latter authors on the grounds that (a) the controversy concerning the existence of an intrinsic planetary magnetic field at Mars is still not settled and (b) existing *in situ* measurements indicate that both plasma and magnetic fields play a significant role in the pressure balance at the surface of the Martian obstacle (at least in the subsolar region).

Energetic particles close to Mars

Intermediate to high energy particle experiments SLED (Solar Low Energy Detector) and LET (Low Energy Telescope), having a composite energy range extending over several tens of keV to several tens of MeV, were included in the plasma segment of the payload of the Phobos-2 spacecraft (McKenna-Lawlor *et al.*, 1990; Marsden *et al.*, 1990). These instruments were operative during the four elliptical orbits of Mars already described above, as well as during multiple circular orbits executed after 18 February, 1989. The only device with particle detection capability in a related part of the spectrum to have previously been flown at Mars, had energy thresholds for electrons and protons of 100 keV and 1 MeV respectively (Vernov *et al.*, 1974).

The various energetic particle measurements made in the close Martian environment by SLED and LET were obtained during a period when the interplanetary medium was in course of transition from solar minimum to solar maximum-dominated conditions. In this connection, Solar Cycle 22 may be deemed to have begun, according to the definition of McKinnon, 1987, in October 1986 (that is in the month after a minimum in the smoothed sunspot number was identified). The energetic particle observations, accordingly, were made in an interval when the particle signatures that dominate periods of low solar activity (due primarily to Co-rotating Interaction Regions (CIRs)), were under gradual replacement by signatures characteristic of the period of solar maximum (due to flare related phenomena).

At the time of the first Elliptical Orbit of Phobos-2 about Mars, the planetary environment was greatly disturbed by the presence of high fluxes of particles, interpreted by McKenna-Lawlor *et al.*, 1991 to be associated with the local transit of a CIR having flare-related particles trapped behind it. The fluxes recorded during this period were such that planetary particle signatures close to the planet could not be separately identified. During the second Elliptical Orbit of Mars there was a long data gap, due to operational constraints, while the spacecraft was flying on the evening side of the planet. During the third and fourth Elliptical Orbits of Mars there were also a number of gaps in the particle measurements when SLED and LET were switched off during spacecraft manoeuvres. Nevertheless, it could be established by McKenna-Lawlor *et al.*, 1992a, 1993, on the basis of SLED data, that energetic particles in the general range 34 keV to several MeV were present close to Mars during each of these two orbits. Those particles attaining energies extending into the MeV range were detected, in each case, on the evening side of the planet.

The present paper aims first to provide a more detailed study of these "evening side" energetic particles through determining where they were located relative to characteristic Martian plasma boundaries identified in data simultaneously recorded by the PWS and by the Magnetometer experiment. Also, the SLED measurements are, herein, supplemented, for the first time, by complementary particle data pertaining to different species recorded by LET which, since it operated over a higher energy range, allows the maximum energies displayed by the more energetic particle enhancements to be investigated. In the light of the additional information thus assembled, it is sought to determine the origin of the energetic "evening side" particles. A general overview of various particle populations recorded by SLED when close to Mars is then provided, and the potential roles of various candidate processes (both local and external to the planet) in accelerating the various populations thus identified in the immediate Martian environment considered.

Instrumentation

A short account is next presented of the SLED, LET, PVS and Magnetometer instruments as a background to the individual measurements presented and discussed in the succeeding section.

The SLED instrument

The SLED detector system comprised two semiconductor telescopes, each incorporating two silicon surface barrier detectors mounted co-axially. One telescope (T2) was protected by a foil, the purpose of which was to prevent low energy ions (<350 keV for protons, <8 MeV for oxygen

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

Channel	T1 (without foil)			
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		

ions) from reaching the detectors, while permitting the passage of electrons. The second "open" telescope (T1) meanwhile recorded both ions and electrons above a threshold determined by detector noise. Count rate differences between the telescopes allow ions and electrons to be distinguished according to a method developed by Anderson *et al.*, 1978. The geometric factor of each telescope was 0.2 cm^2 s ster and the field of view axis, with a 40° apex angle, was in the ecliptic plane at 55° to the west of the sunward direction. Table 1 lists the energy channels pertaining to Telescope 1, data from which are presented in this paper. The Table also provides information concerning the kinds of particle that can be recorded by this detector. The time resolution was 240 s. A more detailed account of the instrument is contained in McKenna-Lawlor *et al.*, 1990.

The LET instrument

The Low Energy Telescope (LET) was designed to monitor the fluxes, spectra and elemental composition of nuclei from hydrogen up to iron in the energy range 1–75 MeV/n, using a double dE/dx vs. E solid state detector telescope. The opening angle of the LET is 46° for the primary coincidence channels. In addition, a small number of low-resolution, single-detector, channels (Channels 1,2,6) are included for which the opening angle is 135°. In the present paper, only data recorded in energy Channel 1 for protons (0.9–1.2 MeV) and in energy Channel 6 for alpha particles (1.0–5.0 MeV/n) are presented.

In order to measure the directional characteristics of ambient particle fluxes, the LET sensor was mounted on a rotating platform. The full rotation range of the platform (175°) was adjusted so that, in its extreme positions, the sensor axis was oriented close to the average direction of the interplanetary magnetic field. This range was divided into steps of 45°. Data accumulation covered a fixed period of 236 s at each of the five positions, and the time resolution was 240 s. In normal operation, the platform executed a complete +60° (with respect to the spacecraft X-axis) → −115° → +60° scan cycle in 40 min, corresponding to two telemetry periods. In one of its extreme positions, the LET instrument viewed in practically the same direction (60° to the west of the Sun line) as did SLED (55° to the west). However, the scan plane of the LET platform was tilted with respect to the ecliptic plane in which the SLED observations were made by 12° in order to avoid obscuration of the field of view by other payload elements. LET is described in detail in Marsden *et al.*, 1990.

The PWS

The PWS measured the plasma density distribution at Mars using a Langmuir probe with a collecting area of 6 cm^2 and an electric antenna formed by two spheres, each 10 cm in diameter and separated by a distance of 1.45 m. The upper frequency range (5 Hz–150 kHz) of the signal detected using the electric antenna was analysed using a set of 24 filters. Various low-frequency channels were also transmitted, including the output of a 0.2–10 Hz filter. The potential difference between one electric sensor and the spacecraft structure was, in addition, monitored to provide information concerning the spacecraft floating potential. A detailed description of the instrument is contained in Grard *et al.* (1989a).

The Phobos-2 magnetometers

MAGMA was one of two triaxial flux-gate magnetometers on the Phobos-2 mission. This instrument had a range of ±100 nT, a resolution of 0.05 nT and returned data at the rate of one vector every 1.5, 2.5, 45 or 600 s, depending on the telemetry mode of the spacecraft. It was mounted at the top of a 3.5 m boom. Data from MAGMA, and from the complementary FGMM magnetometer, were used to estimate the spacecraft field at the location of the MAGMA instrument (< 1 nT). The total offset (sum of the internal offset and the spacecraft field) was calculated from the magnetic field data obtained during spinning and rolling sessions using statistical methods. Further details of the instrument are contained in Aydogar *et al.*, 1989.

Martian plasma boundaries

Before addressing the energetic particle measurements considered in this paper, data recorded aboard Phobos-2 by PWS and MAGMA during Elliptical Orbits 3 and 4 are considered with a view to establishing, in each case, the locations along the spacecraft trajectory where various characteristic Martian boundaries were traversed.

PWS and magnetic data recorded during Orbit 3

Figure 2 presents the spacecraft potential (top panel), as well as middle-frequency (100 Hz to 6 kHz) and low-frequency (25 Hz to 100 Hz) plasma wave activity recorded by PWS during Orbit 3 when close to Mars (8 February, 1989). The "inbound" Bow Shock traversal at 05.35 U.T. is marked by a decrease in spacecraft potential (associated with an accompanying increase in plasma density in the Planetosheath), and by a strong peak in the middle and low frequency plasma waves. A well-defined peak in the spacecraft potential at 05.48 U.T. marks the

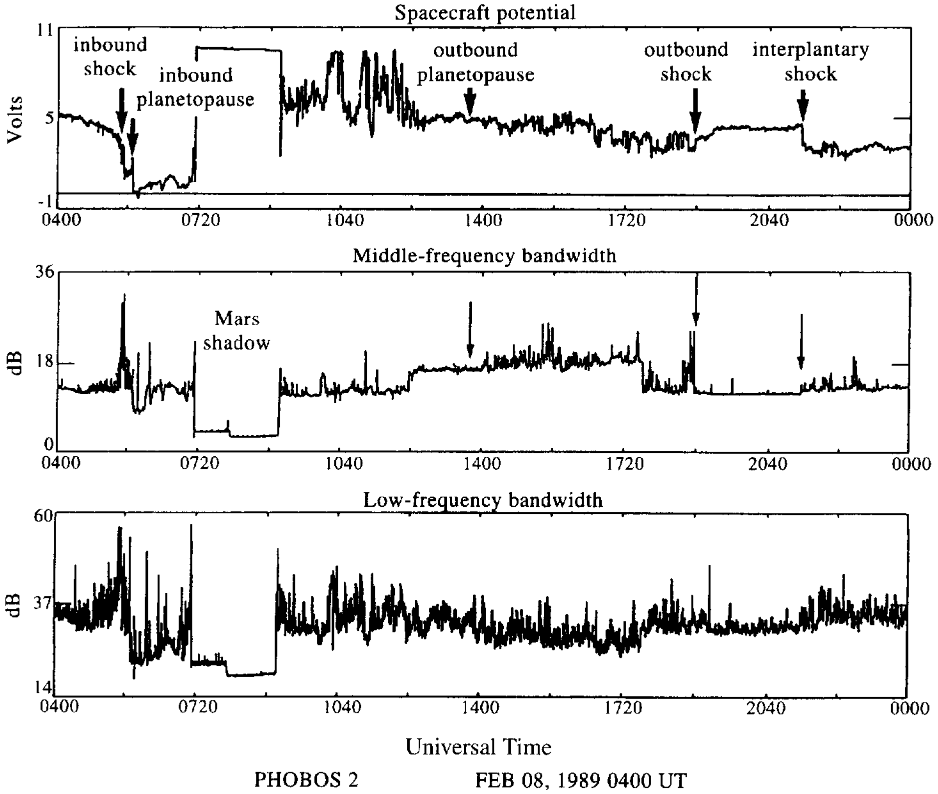

Fig. 2. The spacecraft potential (top), and middle-frequency (100 Hz to 6 kHz) and low-frequency (25 Hz to 100 Hz) bandwidth data recorded by PWS on Phobos-2 in the interval 04.00 U.T., 8 February–00.00 U.T., 9 February, 1989. The times of transit of characteristic plasma boundaries, and the time of arrival at Phobos-2 of a travelling interplanetary shock, are individually indicated

transition of the, inbound, Planetopause, see also Trotignon *et al.*, 1991a, 1991b.

Figure 3 (top) shows the sun–spacecraft line component of the magnetic field B_x, which was recorded on 8 February, 1989 by the MAGMA instrument in tandem with the PWS measurements presented in Fig. 2. The complementary field line components B_y, B_z, and the absolute value of the magnetic field (B) are also displayed. A jump in the magnetic field intensity at 05.35 U.T. (in coincidence with the PWS decrease mentioned above), indicates traversal by the spacecraft of the, inbound, Bow Shock $(\mathrm{BS})_{\mathrm{in}}$. Thereafter, the characteristic signature of strong draping of the magnetic field about the dayside Martian interaction region can be discerned.

Returning now to the PWS record (Fig. 2), the interval of passage of the spacecraft through the shadow of Mars can be deduced through noting where the spacecraft potential was driven negative by the plasma in the absence of compensating photoelectrons. Thereafter, the outbound transition of the Planetopause on 8 February can be inferred to have occurred at ≈ 12.40 U.T. through the subsequent appearance of (a) a general decline in spacecraft potential and (b) a general increase in middle frequency plasma activity—indicating increasing ambient plasma density. Overall, the (outbound) Planetosheath region was characterized by high levels of middle and low frequency plasma wave activity, and by the presence of variable magnetic fields.

In the corresponding magnetic record (Fig. 3) between about 14.00 and 19.00 U.T., the step-like increases and decreases in the total intensity (B) of the magnetic field imply multiple crossings by the spacecraft, when outbound, of the distant Bow Shock. This interpretation is supported by the observation of associated small discontinuities in spacecraft potential, accompanied by variations in plasma wave power (compare with the data of Fig. 2). The final, outbound, Bow Shock traversal into the "unshocked" Solar Wind $(\mathrm{BS})_{\mathrm{out}}$, is marked in the PWS and MAGMA data at 18.58 U.T. by characteristic changes in signature (indicated by arrows on Figs 2 and 3). TAUS plasma measurements (not shown), which are available after 13.25 U.T., support the above identifications.

The magnetic record (Fig. 3) shows that an Interplanetary Shock swept over Phobos 2 at ≈ 21.25 U.T. The passage of this shock can be inferred from the step-like increase recorded at that time in the magnetic field strength (B). This was accompanied (see Fig. 2), by a well defined increase in middle frequency plasma wave activity and by a decrease in spacecraft potential denoting increased plasma density. The plasma signatures are similar to those recorded at the Bow Shock of Mars itself, although they display a somewhat lower amplitude due to the low Mach number that characterizes Interplanetary Shocks.

PWS and magnetic data recorded during Orbit 4

As shown in the PWS data of 11 February (Fig. 4), the inbound Bow Shock crossing was marked (as on 8

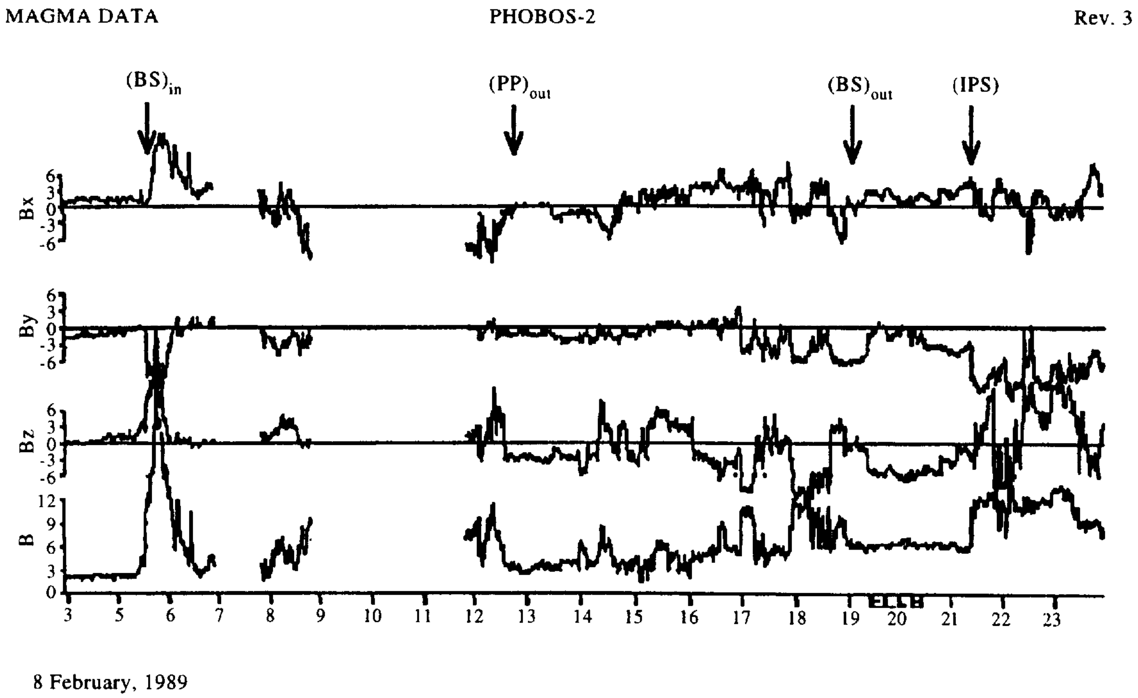

Fig. 3. The sun–spacecraft line component of the magnetic field B_x (top), as well as components B_y, B_z and the absolute value of the magnetic field (B), recorded by the MAGMA instrument on Phobos-2 in the interval 03.00 U.T., 8 February–00.00 U.T., 9 February, 1989. The times of transit of the Inbound Bow Shock $(BS)_{in}$, the outbound Planetopause $(PP)_{Out}$ and the outbound Bow Shock $(BS)_{out}$, as well as the time of arrival at Phobos-2 of a travelling Interplanetary Shock (IPS), are individually indicated

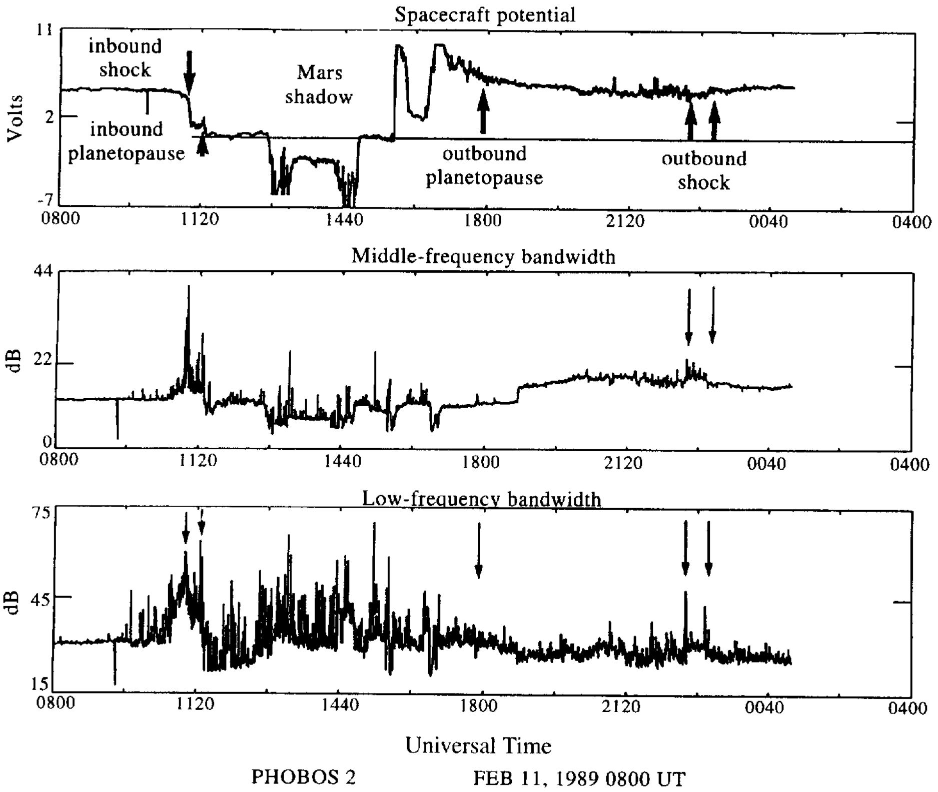

Fig. 4. The spacecraft potential (top), and middle-frequency (100 Hz to 6 kHz) and low-frequency (25 Hz to 100 Hz) bandwidth data recorded by PWS on Phobos-2 in the interval 08.00 U.T., 11 February–04.00 U.T., 12 February, 1989. The times of transit by Phobos-2 of characteristic plasma boundaries are individually indicated

February), by a decrease in spacecraft potential and by an increase in plasma wave activity. Traversal of the, inbound, Planetopause is indicated on the spacecraft potential record (as on 8 February) by a well-defined peak, recorded at 11.24.30 U.T.

As in the previous orbit, the interval of passage of the spacecraft through the shadow of Mars can be deduced through noting where the spacecraft potential was driven negative by the plasma. The gradual decrease in spacecraft potential seen from ≈17.50 UT suggests that Phobos-2 had exited the outbound Planetopause and entered the Planetosheath by at least this latter time.

Identification, using the magnetic record (Fig. 5), of exactly when the outbound Planetopause was traversed is made difficult by a gap in the measurements from 15.40 to 18.20 U.T. The available MAGMA records show, however, a transition from stronger, more tail-like, magnetic fields before the data gap to weaker fields thereafter—which exhibited directions making larger angles with the *X* axis than was the case when the spacecraft was inside the Planetosphere. TAUS observations (not shown) confirm that Phobos-2 was inside the Planetosphere prior to the data gap, and within the Planetosheath after that gap. ASPERA data published by Lundin and Dubinin (1992) confirm that the outbound Planetopause was crossed at ≈16.55 U.T.

The PWS and MAGMA data (as well as TAUS observations, not shown), indicate that multiple crossings of the, outbound, Bow Shock took place between 19.53 U.T. and 23.16 U.T., following which the spacecraft emerged into the external Solar Wind $(BS)_{out}$.

Energetic particle measurements during Orbit 3

Panel 1 of Fig. 6 (top) shows the pitch angle of the central axis of the SLED field of view calculated from magnetic measurements for the period 04.00–20.15 U.T, on 8 February, 1989 (i.e. while Phobos-2 was close to Mars during Orbit 3). Panels 2 and 3 show corresponding particle fluxes recorded by SLED in Channel 1 (34–51 keV) and Channel 2 (51–200 keV) of Telescope 1. Panel 4 shows alpha particle fluxes recorded by LET in its Channel 6 (1.0–5.0 MeV/n) and Panel 5 shows fluxes recorded in five different directions by LET in its proton Channel 1 (0.9–1.2 MeV). The latter traces are, for clarity of presentation, displayed displaced from each other. The vertical scale provided refers to the lowest trace. The upper four profiles would have been superimposed on the bottom signature, were they not displaced in the figure by arbitrary amounts to reveal how these profiles differ from each other. We can infer from the LET records that conditions in the inbound and outbound Solar Wind remained essentially unchanged on this day while the spacecraft traversed the close Martian environment.

Inbound, the T1 Channel 1 (34–51 keV) SLED record shows a very clear enhancement which commenced when the spacecraft crossed the inbound Planetopause $(PP)_{in}$. The particle data secured during the remainder of the orbit are fragmentary, owing to the switching off of both SLED and LET during spacecraft manoeuvres.

The SLED records, T1 Channels 1 and 2, show a progressive rise in flux from about 14.00 U.T. Two large maxima were recorded superimposed on this general increase

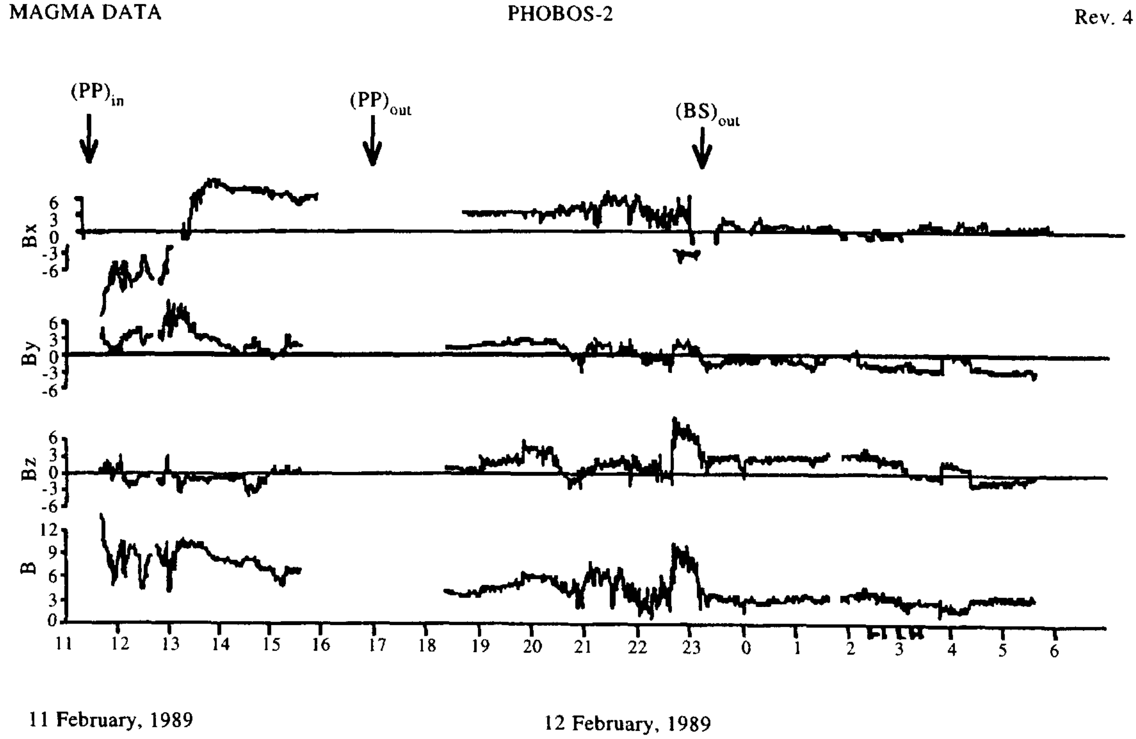

Fig. 5. The sun–spacecraft line component of the magnetic field B_x (top), as well as components B_y, B_z and the absolute value of the magnetic field (B), recorded by the MAGMA instrument on Phobos-2 in the interval 11.00 U.T., 11 February–06.00 U.T., 12 February, 1989. The times of transit by the spacecraft of the inbound Planetopause $(PP)_{in}$, the outbound Planetopause $(PP)_{out}$ and the outbound Bow Shock $(BS)_{out}$, are individually indicated

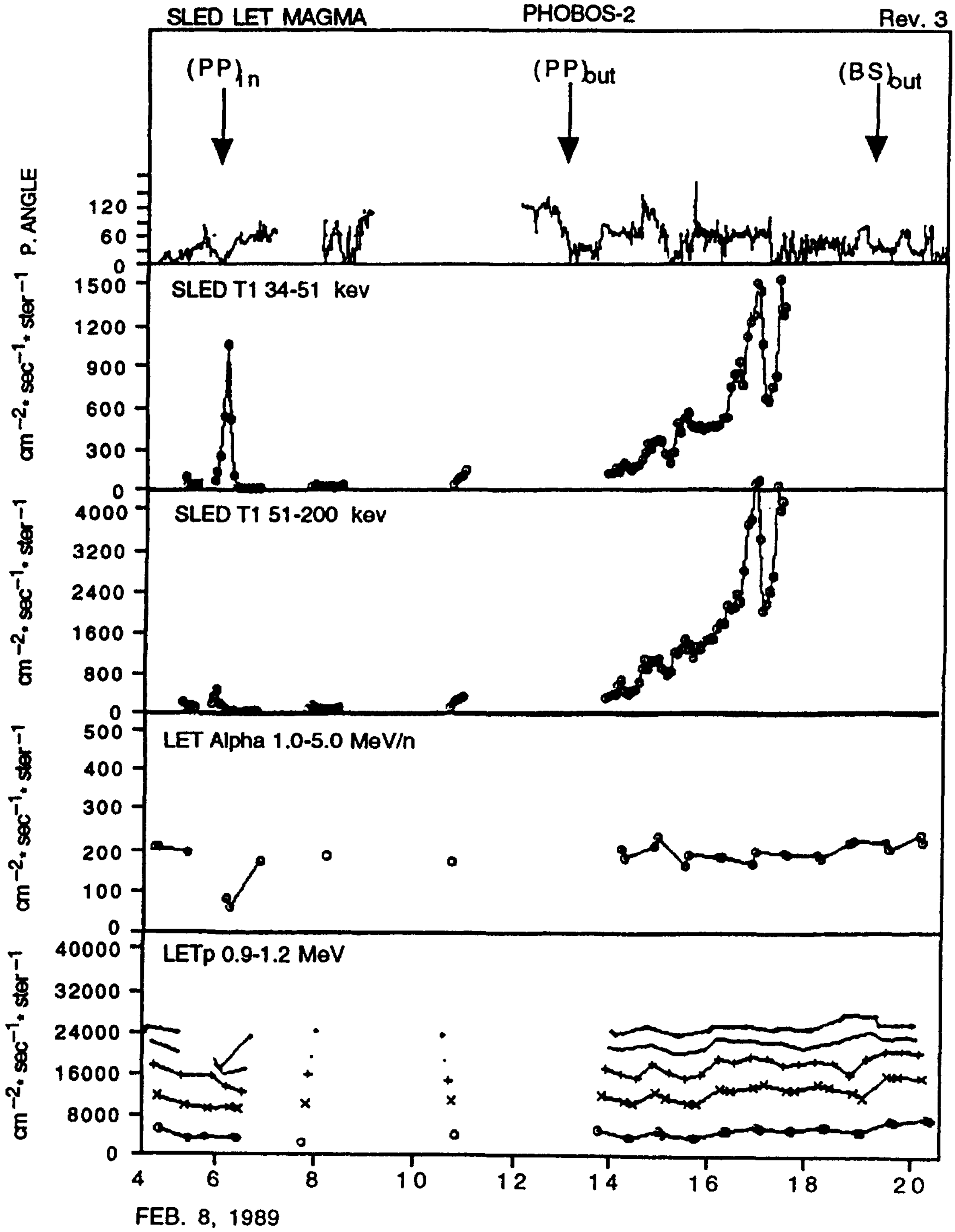

Fig. 6. Panel 1 (Top); pitch angle of the central axis of the SLED field of view calculated from the magnetic measurements from 04.00–20.15 U.T., 8 February, 1989. Panels 2 and 3: corresponding measurements of particle fluxes recorded in SLED T1 Channels 1 and 2 (34–51 keV and 51–200 keV). Panels 4 and 5: corresponding alpha particle fluxes (1.0–5.0 MeV/n) and proton fluxes in five directions (0.9–1.2 MeV) recorded by LET. The times of transit by the spacecraft of the (inbound) Planetopause $(PP)_{in}$, the outbound Planetopause $(PP)_{out}$ and the outbound Bow Shock $(BS)_{out}$ are individually indicated

just before the instrument was switched off by the spacecraft close to 17.15 UT. These maxima could be distinguished in each of the first four channels of the instrument and were, therefore, produced by particles in the energy range 34 keV–≥0.6 MeV. LET data, within the same interval, showed very slight variability in the proton channel record (0.9–1,2 MeV), but no. large flux enhancements were detected. The LET alpha particle channel (1.0–5.0 MeV/n) also showed no significant enhancement.

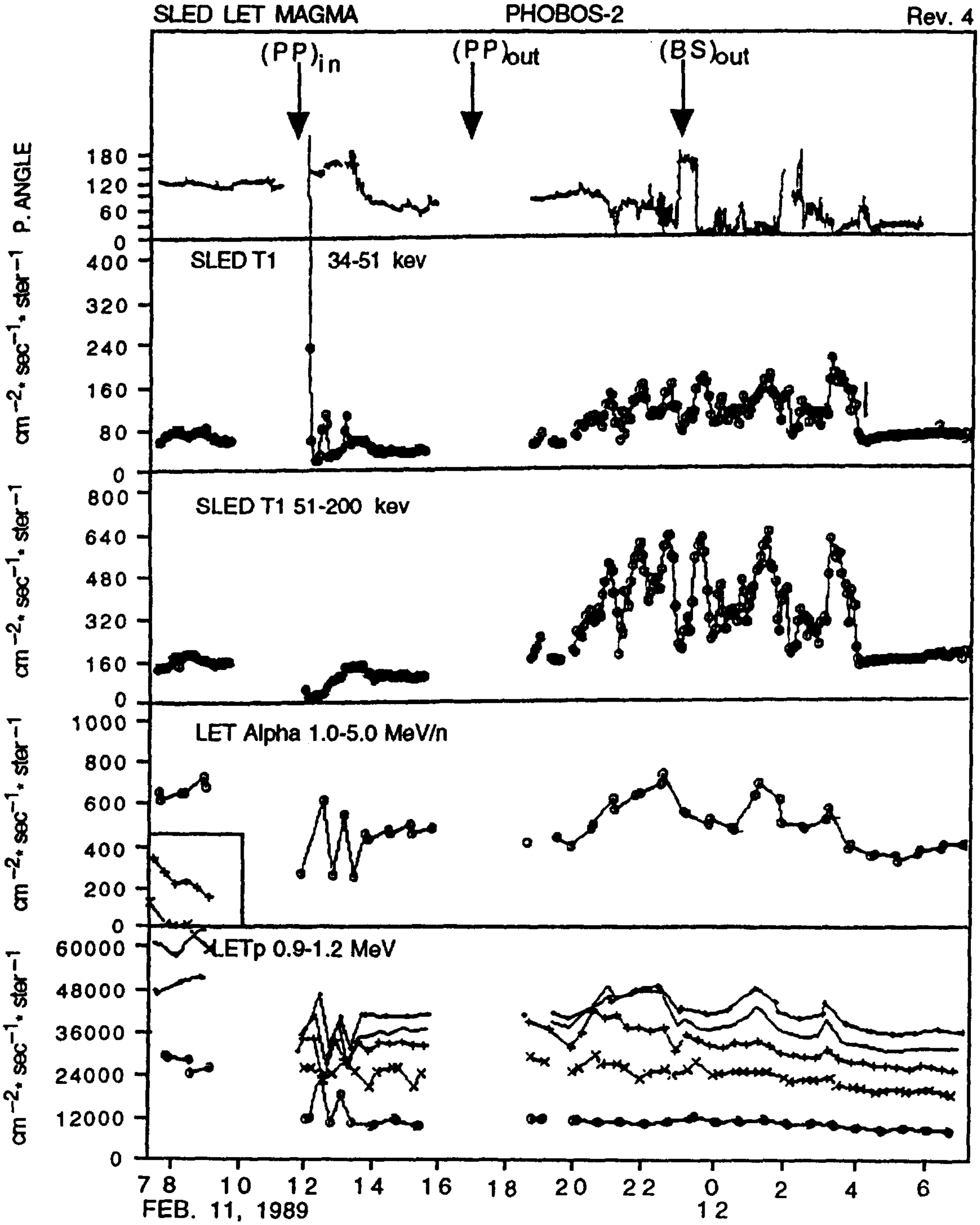

Fig. 7. Panel 1 (top): pitch angle of the central axis of the SLED field of view calculated from the magnetic measurements from 07.00 U.T., 11 February to 07.00 U.T., 12 February, 1989. Panels 2 and 3: corresponding measurements of particle fluxes recorded in SLED T1 Channels 1 and 2 (34–51 keV and 51–200 keV). Panels 4 and 5: corresponding alpha particle fluxes (1.0–5.0 MeV/n) and proton fluxes in five directions (0.9–1.2 MeV) recorded by LET. The times of transit by the spacecraft of the inbound Planetopause $(PP)_{in}$, the outbound Planetopause $(PP)_{out}$ and the outbound Bow Shock $(BS)_{out}$ are individually indicated

Energetic particles recorded during Elliptical Orbit 4

Figure 7 (top) shows pitch angle data for SLED estimated for the interval 07.00 U.T., 11 February–07.00 U.T., 12 February, 1989 during Elliptical Orbit 4. Corresponding energetic particle records obtained by SLED and LET are displayed using the format adopted (see above) in Fig. 6.

A high peak in particle fluxes in the SLED T1, Channel 1, data was present from before 12.00 U.T. when the spacecraft was just inside the inbound Planetopause.

Following a gap due to spacecraft manoeuvres, the SLED instrument recorded a significant flux enhancement from approximately 19.00 U.T. on 11 February up to approximately 04.00 U.T. on 12 February, 1989 (see

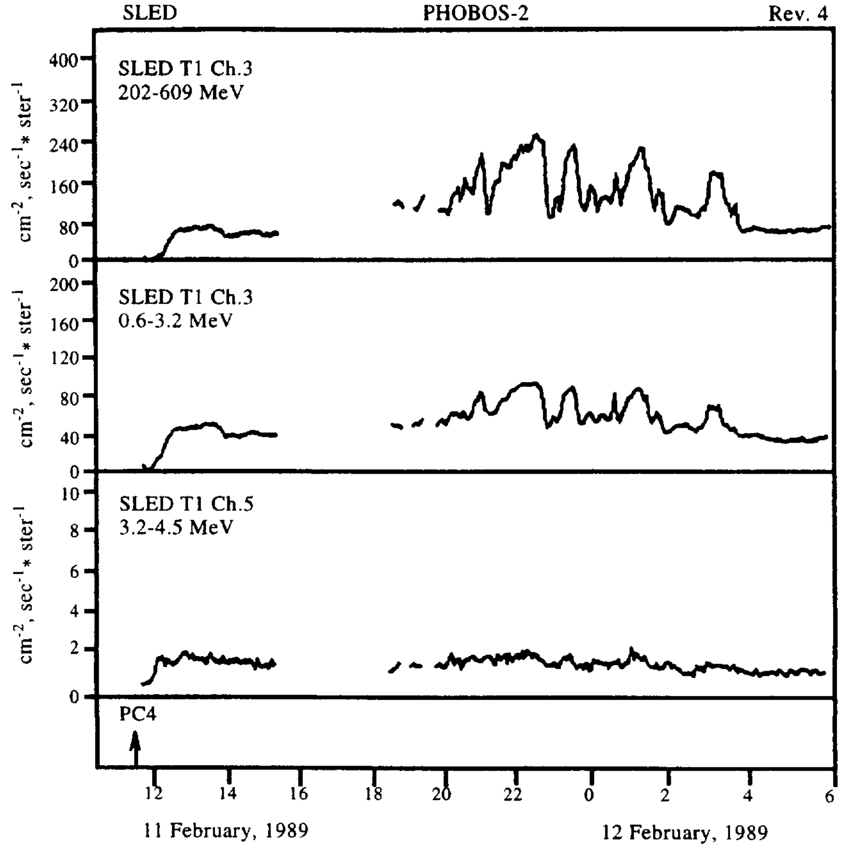

Fig. 8. Particle fluxes recorded by SLED in T1, Channel 3 (202–609 keV), Channel 4 (0.6–3.2 MeV) and Channel 5 (3.2–4.5 MeV) during Elliptical Orbit 4 from 11.45 U.T., 11 February–06.00 U.T., 12 February, 1989. The time of pericentre passage (PC4) is indicated by an arrow

Panels 2 and 3). Figure 8 compares variations in the particle data recorded by SLED in the interval 11.45 U.T., 11 February–06.00 U.T., 12 February, 1989 in Channel 3 (202–609 keV), Channel 4 (0.6–3.2 MeV) and Channel 5 (3.2–4.5 MeV) of Telescope 1. The data of Channels 3 and 4 show several well defined maxima during the large particle enhancement from $\approx$ 19.00 U.T. on 11 February. The data of Channel 5 show very minor, although identifiably related, variations. We can thus infer that particles with energies up to 3.2 MeV participated in the large particle increase.

The LET particle records presented in Fig. 7 show a well defined increase in the fluxes recorded in alpha Channel 6 (1.0–5.0 MeV/n) in the same interval (see above) during which the SLED record was enhanced. No corresponding signature was recorded in alpha Channel 7 (1.9–4.0 MeV/n). This indicates that alpha particles were accelerated to $\geq$ 4 MeV, but to less than 7.6 MeV. In Channel 6, the particle record is characterized by three well defined maxima. Before these maxima were produced, alpha particle fluxes recorded by LET upstream of the inbound Bow Shock had, by $<$ 19.00 U.T. on 11 February, attained a level comparable with that displayed at $>$ 04.00 U.T. on 12 February.

Panel 5 shows complementary flux variations in LET proton Channel 1 (0.9–1.2 MeV) recorded in five different directions. As in Fig. 6, the vertical scale refers to the bottom trace and the upper profiles, which would otherwise have been superimposed, are displayed displaced by arbitrary amounts to allow differences between the individual records to be recognized. The upper trace corresponds closely with the SLED look direction, and the bottom trace refers to the opposing look direction. The upper traces display variations characterized by the presence of three maxima and appear similar to the record obtained by LET in alpha particles (three maxima are particularly well marked in the upper three traces). The lowest trace does not show this pattern.

Discussion of "evening side" energetic particle measurements recorded during Orbit 3

As indicated in Table 1, more than one species of particle can stimulate the SLED detectors to produce signatures in individual energy channels of the instrument. It is thus necessary to seek to identify the species of the particles recorded when close to Mars.

The lowest energy channel of SLED (T1) responds, in the case of protons, to $\sim$30–50 keV of energy deposited in the solid state detector by an incoming particle (see Table 1). In the case of heavier ions, owing to the pulse height defect in silicon detectors, the deposited energies are less than the primary energies of incoming particles, Keppler, 1978. Pre-flight calibration, has shown that the first four channels of SLED (T1) respond as shown in Table 1 to water group ions.

Measurements made by the ASPERA experiment showed that, prior to crossing the inbound Bow Shock at Mars, intense (> 1.5 orders of magnitude) increases in the O^+ ion density were recorded. There was, simultaneously, a drop in the density of H^+ ions, Lundin *et al.*, 1989. Also, oxygen ions ($\approx 10^{-1}\,O\,cm^{-3}$) were inferred by Kirsch *et al.*, 1991, based on a model developed by Ip, 1990a, to be present at large distances ($5\text{–}6 \times 10^4$ km) upstream of Mars. As is well known, such oxygen ions would be picked up by the convection electric field ($E = -V \times B$) of the Solar Wind and accelerated to a maximum energy corresponding to twice the Solar Wind velocity in the anti-sunward direction. The maximum energy attainable through this pickup process is given by the expression

$$E_{\max} = 2MV^2 \sin^2 \phi$$

where M represents the mass of the ions; V is the Solar Wind velocity and ϕ is the angle between the Solar Wind and the magnetic field direction. The Solar Wind measured at Mars by the TAUS experiment was $500\,km\,s^{-1}$ during the four elliptical orbits executed by Phobos-2 during February, 1989. The maximum pickup energies that could be attained by ions representative of the Martian environment, e.g. H^+, O^+, O_2^+ and CO_2^+ can thus be calculated, for $\phi = 90^\circ$ and $V = 500\,km\,s^{-1}$, to be 5.25, 100, 200 and 275 keV respectively. H^+ pickup ions would not, under the prevailing interplanetary conditions, have had sufficient energy to stimulate the channels of SLED (see Table 1). Given the fact that CO_2^+ ions have a significantly lower scale height than is exhibited by O^+ and O_2^+ it can be inferred that mainly oxygen pickup ions could have been recorded by the SLED instrument at Mars. See, in addition, the demonstration by Afonin *et al.*, 1991 of the capability of hot oxygen ions to attain the Phobos-2 altitude.

As indicated in Table 1, the particle signatures recorded by SLED in T1 (Channels 1–4) could also have potentially been produced by a mixture of electrons and positive ions. However, a comparison of the data of T1 and T2 using the method of Anderson *et al.*, 1978, showed that, in fact, enhanced electron fluxes were not present in the measurements. Also, no electrons were recorded above the general background by LET in its Channel 6 (350 keV–1.5 MeV electrons).

The response of LET to oxygen ions is determined through a combination of the (two) foils covering the entrance aperture and the discriminator thresholds for the single detector channels. It is estimated by the LET experimenters that the minimum energies required in order that oxygen ions would trigger the respective discriminators is in excess of 20 MeV, Marsden, 1997. It is noted in this connection that no indication of the presence of O^+ ions was detected by LET in its Channel 12 (3.2–7.5 MeV/n) in the close Martian environment.

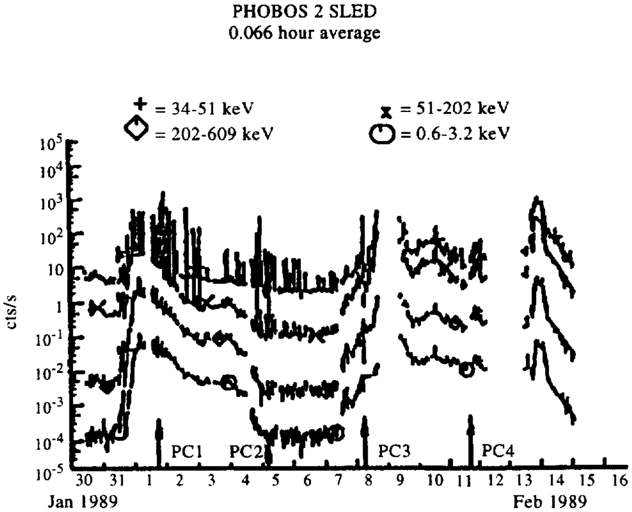

Fig. 9. Overview of measurements made in T1 (Channels 1–4) of SLED during four elliptical orbits of the planet (30 January–15 February, 1989). PC1, PC2 etc. refer to the first pericentre passage, second pericentre passage etc.

Consideration now of the energetic particles detected by SLED over the period 7–15 February (see Fig. 9) reveals that the enhancing fluxes recorded between 14.00 and 17.00 U.T. on 8 February formed part of a general interplanetary enhancement that first began (as recorded in Channels 1–4) at about noon on the previous day and continued until the SLED observations ended on 15 February. The energies of the particles in this population were too high to have been attained by the pickup process acting alone (see Table 1), and it is suggested that the rising fluxes recorded by SLED on 8 February from ≈ 14.00 U.T. were associated, primarily, with the arrival of energized particles travelling upstream of an Interplanetary Shock that reached Phobos-2 at 21.25 U.T. (see Fig. 3). Such shocks typically carry with them a region of enhanced energetic fluxes (the foreshock), which extends for many hours ahead of the actual shock see for example Cane *et al.*, 1988.

LET measured a proton/alpha ratio of 50–80 throughout the large scale enhancement (up until 15 February). It should be noted that, at no time did the measured ratio come anywhere close to the value of 10–20, which is typical of CIRs. Values of 0.07 for Fe/O and 0.4 for C/O were also consistently measured. These ratios are representative of Solar Energetic Particle (SEP) abundances (neither value is CIR like), see Marsden *et al.*, 1991 and references therein. Such Fe/O ratios are generally interpreted to result from the acceleration of solar ions by large scale shock waves propagating outwards through the corona in association with "Gradual Energetic Solar Particle Events", as defined by Reames, 1993.

The two large peaks observed just before SLED was switched off require further consideration. The magnetic data show that the 15–20 min dip in the SLED flux at ≈ 16.50 U.T. was spatially associated with a double Bow Shock transit (one of several Bow Shock transits recorded by MAGMA before the spacecraft finally emerged into the Solar Wind at 18.58 U.T.), and it is interesting to consider whether the enhanced fluxes recorded immediately before, and immediately after, this dip might have been due to Bow Shock accelerated particles, viewed twice by SLED in consequence of the double traversal of the shock front executed by the spacecraft.

In the next section, the energy spectra of particles recorded within the two peaks are compared to see if they might comprise the same particle population. These spectra are then separately compared with spectra measured

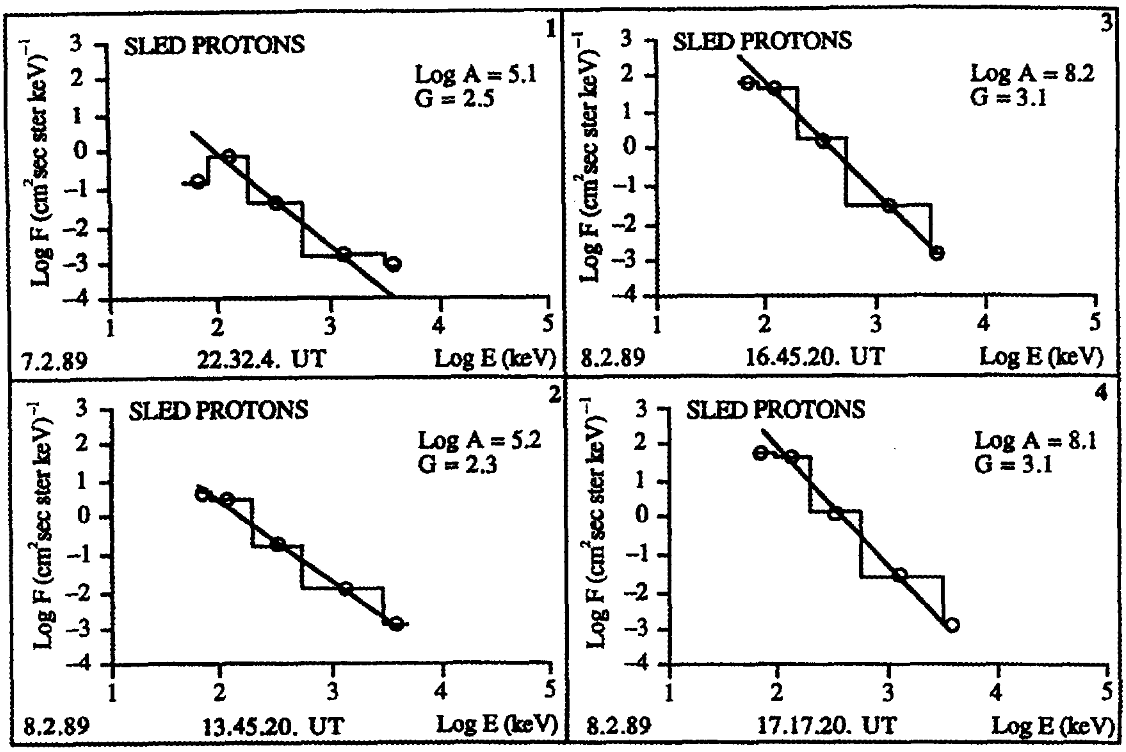

Fig. 10. Differential energy spectra recorded by SLED at various locations along the trajectory of Phobos-2 on 7 and 8 February, 1989 (integration time 240 s). For details see Table 2. A fit to these data on the assumption of a power law $F = A \times E^{-G}$, is, in each case provided

within samples of those particles contributing to the general background enhancement.

Spectra of energetic particles recorded during Orbit 3

It was observed when studying general aspects of the spectra of particles recorded by SLED in the Solar Wind that, at low energies, considerable variability was consistently present in the data and that, very often, a "maximum" was recorded at the boundary between Channel 1 and Channel 2 data ($E \approx 50$ keV). In such cases, the spectrum at low energies frequently appeared to "turn over" while, at other times, a power law was obeyed. Even in the latter instances, however, the data of Channel 1 were always found to he lower in counts than would be "expected" given the prevailing trend.

Figure 10 presents examples of differential energy spectra measured close to Mars by SLED on 7 and 8 February, 1989 using the basic 240 s integration time of the instrument. Associated information is provided in Table 2. Because of the variability already noted in the data of Channel 1, and the stable behaviour found to be a characteristic of the data of Channel 5 (E = 3.2–4.5 MeV), a fit is provided in each case to the data of Channels 2–4 on the assumption of a power law $F = A \times E^{-G}$.

As shown in Table 2 and in the plots of Fig. 10, a spectrum obtained in the upstream interplanetary medium at 22.32.04. U.T. on 7 February (when the general rise in background fluxes observed on 8 February had already begun), and another spectrum obtained considerably later at 13.45.20 U.T. on 8 February when the spacecraft was traversing the outbound Planetosheath, were closely similar, suggesting that the same background population was sampled on each occasion. The large flux enhancements on 8 February at 16.45.20 U.T. and at 17.17.20 U.T. provide, on the other hand, spectra that are similar to each other, while appearing significantly different from

Table 2. Details concerning differential energy spectra measured at various locations along the trajectory of Phobos-2 during 7 and 8 February, 1989, each of which, see Fig. 10, was fitted with a power law ($F = A \times E^{-G}$)

Plot	Date, 1989	(Time) U.T.	Log A	$(-)G$	Location
1	7 February	$22^{h}.32^{m}.04^{s}$	5.1	2.5	In the (upstream) Solar Wind after a general background enhancement had commenced
2	8 February	$13^{h}.45^{m}.20^{s}$	5.2	2.3	While traversing the outbound Planetosheath during ongoing activity
3	8 February	$16^{h}.45^{m}.20^{s}$	8.2	3.1	Within the first peak
4	8 February	$17^{h}.17^{m}.20^{s}$	8.1	3.1	Within the second peak

the spectra of the particles measured at 22.32.04 U.T. on 7 February and at 13.45.20 U.T. on 8 February. It is thus very likely that the "peaks" represent a population of Bow Shock accelerated particles seen twice, superimposed on a (generally enhancing) particle background.

Two Bow Shock acceleration mechanisms may be considered to explain the enhanced fluxes, namely Diffuse Acceleration (which, at the Earth is most effective for quasi-longitudinal or longitudinal shocks (with $\phi_{NB} = 0°$–$45°$), and Shock Drift Acceleration, which is correspondingly most effective for quasi-perpendicular or perpendicular shocks (with $\phi_{NB} = 45°$–$90°$), where ϕ_{NB} is the angle between the shock normal and the mean upstream magnetic field.

Diffuse Bow Shock acceleration is limited by the dimensions of the system involved and, since the Martian Bow Shock is much smaller than that of the Earth, it was pointed out by Ip (1990b) that the diffuse acceleration mechanism would not, in fact, be expected to produce high energy particles at this planet.

Shock Drift Acceleration of ions originating upstream of the Bow Shock can, on the other hand, 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 $V \times B$ electric field (where V is the plasma bulk velocity and B is the magnetic field) (see for example Chen and Armstrong, 1974; Armstrong *et al.*, 1985; Krimigis and Sarris, 1985 and Gosling and Robson, 1985). As shown by Decker (1983), spike-like particle enhancements can be produced owing to Shock Drift Acceleration at a quasi-perpendicular shock.

In the particular case of the high speed Solar Wind pertaining during Elliptical Orbit 3 at Mars ($V \approx 500\,\mathrm{km\,s^{-1}}$. see above), taking $E_y = -V_x B_z$ and a representative value for $B_z \approx 6\,\mathrm{nT}$, the corresponding value of E_y along the shock front is of the order of $3.5\,\mathrm{mV\,m^{-1}}$. If now we assume for the Martian Bowshock a diameter of $5R_M$ and take an effective acceleration length of 10^3 km, it can be estimated that protons and O^+ ions would gain an energy of ≈ 35 keV, while O_2^+ ions would gain ≈ 70 keV in a single Bow Shock encounter.

Assuming a typical Parker spiral angle of 57° it was shown by Trotignon *et al.* (1991a) that ϕ_{NB} was almost equal to 70° for the inbound, and to 0° for the outbound, Martian Bow Shock crossings. Thus, on the average, quasi-perpendicular shocks were present near the dusk terminator while quasi-parallel shocks were present near the dawn terminator. As is well known, energized ions can, under favourable circumstances, undergo reflection so that they re-encounter the acceleration region associated with a particular shock. In the present circumstance, such a Fermi Acceleration process could be realized in cases where the interplanetary magnetic field is aligned to form a quasi-parallel shock ($\phi_{NB} < 45°$) (Axford *et al.*, 1977 and Scholer, 1985). At the outbound shock at Mars, ions which had already gained energy from the pickup process, or in association with background solar activity, could not only be further energized owing to a single Bow Shock encounter, but could also potentially be reflected so as to encounter the acceleration region again multiple times.

It is pertinent to note here that, during the period 18 February–26 March, 1989 while Phobos-2 was in Circular Orbit about Mars, SLED on many occasions recorded, when the interplanetary conditions were relatively quiet, beams of energetic particles at the Terminator Shocks. Sometimes these Bow Shock associated particle increases were recorded during both the inbound and outbound shock traversals; in other cases enhancements occurred at the inbound or at the outbound shock alone; sometimes no particle increases were recorded in association with either Bow Shock transit. These different kinds of observation were a function of the prevailing magnetic circumstances (Afonin *et al.*, 1991). See also the predicted behaviour of reflected particles at quasi-perpendicular shocks (Moses *et al.*, 1988). The enhancements recorded appeared, primarily, in T1, Channel 1 but, sometimes, minor enhancements also appeared in T1, Channel 2. The maximum energy attained by the particles in all of these events was < 200 keV and, in the majority of cases, was ≈ 50 keV (see Table 1). These values are very substantially lower than the energy (≈ 600 keV) attained by those particles recorded (see above) at the outbound Bow Shock during Elliptical Orbit 3. It can thus be inferred that the ions energized at the Bow Shock on this latter occasion (due to Shock Drift, possibly supplemented by Fermi Acceleration), originated in the ambient population of particles associated with the Gradual Solar Energetic Particle Event and associated travelling shock which (see above) contributed to the elevated particle background present at Mars on 8 February, 1989.

Modeling the location of the distant Martian Bow Shock

It is interesting to consider the location of the distant, double, Bow Shock crossing identified during elliptical Orbit 3 in SLED particle data, in relation to already published models developed by various authors to predict the position of such distant shocks, all of which are based on plasma and magnetic field data measured aboard various spacecraft.

Slavin and Holzer (1981) developed a procedure for modeling the shape and location of the Martian Bow Shock according to which this shock is represented by a conic section whose focus is allowed to move along the X axis until the best fit to the available experimental data is found. Expressed in polar coordinates with respect to a focus located at $X = 0$ (and neglecting aberation), the equation for the shock surface is given by

$$r = L/(1 + e\cos\phi)$$

where r is the distance from the focus to the shock at an angle ϕ to the X axis; L is the semi-latus rectum and e is the eccentricity of the conic surface. Fitting is achieved by employing a series of linear least squares computations to find both (e, L) and the rms deviation as a function of the location of the focus (see McKenna-Lawlor and Afonin, 1992b).

Several bow shock models constructed using this approach have already been published (see Russell, 1977; Slavin and Holzer, 1981; Schwingenschuh *et al.*, 1990; Slavin *et al.*, 1991 and Trotignon *et al.*, 1991b). For the present text, the various published models were (a) reconstructed using the parameters listed in Table 3 (which

Table 3. Bow shock models: based on plasma wave system and magnetometer data

Model no.	Reference	Spacecraft	Number distant BS crossings	e	$L(R_{\mathrm{Mars}})$	$X_0(R_{\mathrm{mars}})$
1	Russell, 1977	Mars 2,3, 5	11	0.99	3.00	0.0
2	Trotignon *et al.*, 1991b	Phobos-2	26	0.65	2.66	0.0
3	Trotignon *et al.*, 1991b	Phobos-2	26	0.95	2.17	0.5
4	Slavin and Holzer, 1981	Mars 2,3,5	14	0.94	1.94	0.5
5	Schwingenschuh *et al.*, 1990	Phobos-2	100	0.85	2.72	0.0
6	Slavin *et al.*, 1991	Mariner 4 Mars 2,3,5 Phobos-2	118	1.02	2.04	0.55

correspond, with very minor modifications, to those adopted in the original publications), and (b) individually fitted, as indicated in Table 3, to various single and composite data sets based on Bow Shock crossings observed in plasma and magnetic field data secured aboard Mariner-4, Mars 2, 3 and 5 and Phobos-2. The models of the distant Bow Shock position thus reconstructed are presented in Fig. 11, overlaid on a plot of Elliptical Orbit 3 presented in cylindrical coordinates. The frame of reference used is the Mars centred solar orbital system (MSO) in which the X axis is taken to be positive towards the Sun; Z is deemed to be normal to the plane of the orbit of Mars and the positive direction is to northwards. The vertical axis graphs distance from the X axis.

When compared with the SLED observation, the closest prediction of the location of the deep tail Bow Shock crossing on 8 February was that of Trotignon *et al.*, 1991b (Model 3 in Table 3). This was based on 26 such crossings recorded by the Plasma Wave System on Phobos 2. The next closest prediction was that of Slavin *et al.* (1991) (Model 6 in Table 3). This Model was based on a sample of 118 crossings assembled from the data of five different spacecraft (including Phobos-2), and it provided a prediction coincident with the time of the last traversal of the (outbound) Bow Shock recorded in magnetic data at 18.58 U.T. These comparisons suggest that, while considerable latitude is available for varying the parameters employed in predicting distant crossings (see Table 3), to achieve successful modeling the value adopted for the eccentricity (e) of the Bow Shock should be of the order of 1.00.

Up until now, Bow Shock transition data used in modeling the Solar Wind interaction with Mars, have been based only on plasma and magnetic field measurements. The particle beams consequent on Bow Shock acceleration, detected by SLED when favourable magnetic conditions pertained during Circular Orbits about the planet consisted, in many cases, of intense narrow spikes, having individual widths that were very much less than the ion gyroradius under the local conditions pertain-

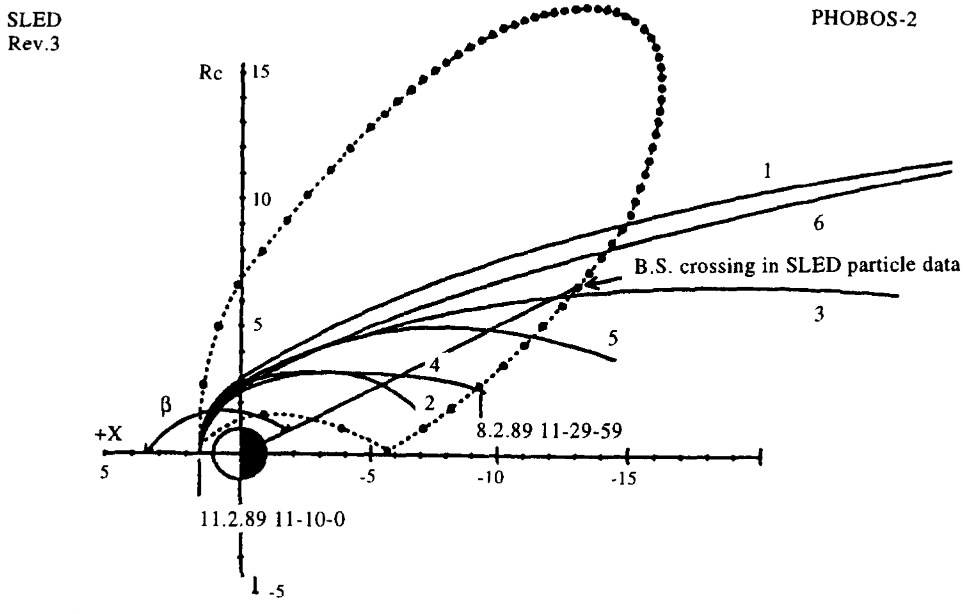

Fig. 11. Plot, presented in the Mars centred solar orbital system (MSO), of Elliptical Orbit 3 of Phobos-2 about the planet, with timing marks applied every 60 min. Six models of the Martian distant Bow Shock position, based on the parameters and observations listed in Table 3, are overlaid on this diagram. The measured location of the distant Bow Shock identified in SLED particle data using the *first particle peak* recorded during a double Bow Shock transit at ≈16.30 U.T. on 8 February is indicated (see also Fig. 6 which shows a dip in particle flux at 16.50 U.T. followed by a second peak at ≈17.15 U.T.)

ing. In some cases, these flux increases displayed a width approximately equal to the ion gyroradius. The rich, and spatially precise, data set thus provided can now be used to confirm, and in some cases provide previously uncharted instances of, Martian Bow Shock crossings. As such, they can be exploited to make a significant, and precise, contribution to those data sets already used in the literature in modelling the Solar Wind interaction with Mars.

Origin of the "evening side" energetic particles recorded during Orbit 4

During Orbit 4, while Phobos-2 was on the evening side of Mars, a well defined enhancement in particles began at approximately 19.00 U.T. on 11 February, 1989, shortly after the spacecraft had crossed the outbound Planetopause at 16.55 U.T. (compare the particle data presented in Fig. 7 with the corresponding PWS and magnetic data contained in Figs 4 and 5). This enhancement endured through multiple crossings by the spacecraft of the (distant) Martian Bow Shock, from 19.53 to 23.16 U.T., and the level returned at 04.00 U.T. on 12 February, 1989 when the spacecraft was already deep in the prevailing Solar Wind, to a value close to the level pertaining before ≈ 19.00 U.T. on the previous day.

The enhancement concerned appears modest when compared with the factor of ≈ 100 increase in intensity on which it is superimposed (see Fig. 9) and which, as already discussed in relation to observations made during Elliptical Orbit 3, can be attributed to particles produced in association with a Gradual Solar Energetic Particle Event accompanied by a travelling shock. The lack of velocity dispersion that marks the commencement and end of this enhancement can be ascribed to the passage of a particular particle population that formed an identifiable feature (see also below), within this, ongoing, complex event, see analogous observations made aboard Ulysses during similar activity recorded during March 1991, Sanderson *et al.*, 1992.

The SLED data presented in Fig. 8 show that the maximum energies attained by protons within this population were in the range 3.2–4.5 MeV. Alpha particle fluxes with energies up to at least 4 MeV were simultaneously recorded by LET, see Fig. 7. This latter record was characterized after 19.00 U.T. on 11 February by a profile showing a triple maximum, similar to that recorded by this same instrument in its proton channel 1 (0.9–1.2 MeV). It is noted with regard to making comparisons between SLED and LET data, that the LET channels provided single detector measurements featuring a very wide acceptance angle (135°). Given the 45° steps of the rotating platform, very significant smearing of any anisotropies present in the data would be introduced, and this can explain why the LET measurement did not record the same number of peaks in the data as did SLED.

The directional data provided by LET indicate, when compared with the magnetometer records, that enhanced particle fluxes within the Planetosheath were primarily flowing along the magnetic field direction (away from the Sun), and that almost no particles were moving in the contrary direction (i.e. the pitch angle distribution was nearly isotropic, but with an almost empty backward cone of half angle 40°–50°).

Spectra of energetic particles recorded during Elliptical Orbit 4

Figure 12 presents energy spectra based on SLED data measured at different locations along the spacecraft trajectory during Elliptical Orbit 4. The first spectrum was taken at 09.05.26 U.T. on 11 February in the upstream Solar Wind. The second spectrum was obtained at 14.40.21 U.T. on 11 February while the spacecraft was traversing the Planetosphere. These spectra, which appear generally similar, were obtained during the decline of an earlier enhancement within the, ongoing, background solar particle event (see Fig. 9).

A sequence of similar spectra obtained at different locations within the particle enhancement that commenced at ≈ 19.00 U.T. suggests that the particles thus sampled were all part of a population contained within a spatially well-defined structure, the outbound boundary of which was traversed at 04.00 U.T. on 12 February (compare with the significantly different spectrum obtained at 05.33.14 U.T in the still disturbed Solar Wind external to this feature). See also Table 4.

The quasi-periodic (35–40 min) intensity variations displayed by the enhanced particle fluxes recorded between 19.00 UT, 11 February and 04.00 U.T., 12 February, show no particular correlation with contemporary pitch angle data computed using MAGMA data (Fig. 7). The particle fluxes are thus deduced not to have been strongly coupled to the local planetary magnetic field, and the variations observed are deemed to constitute a characteristic of the transitory particle enhancement itself, rather than represent an influence of the background Martian environment.

Energetic particles recorded on the sunward side of Mars

During Elliptical Orbit 3, starting at approximately 05.48 U.T., a flux enhancement was recorded as the spacecraft crossed the Planetopause on the subsolar side (see Fig. 6). This enhancement endured for approximately 26 min. During Elliptical Orbit 4 (Fig. 7), the end of a complementary enhancement was recorded at the same general location by the SLED instrument (following a data break occasioned by spacecraft manoeuvres). A flux enhancement was also detected by SLED during Elliptical Orbit 2 at the time of an inbound Planetopause crossing reported by the PWS and Magnetometer Teams (Afonin *et al.*, 1989). Owing to the presence of large particle fluxes associated with the passage of a CIR, no corresponding information concerning the presence or absence of this feature was derived from the SLED data obtained during Elliptical Orbit 1 (McKenna-Lawlor *et al.*, 1992a). Overall, flux enhancements, displaying energies up to ≈ 225 keV were observed at the same location over a period of 8 days at an altitude of ≈ 900 km above Mars.

Several possible explanations for this long-lived enhancement have already been offered by Afonin *et al.*

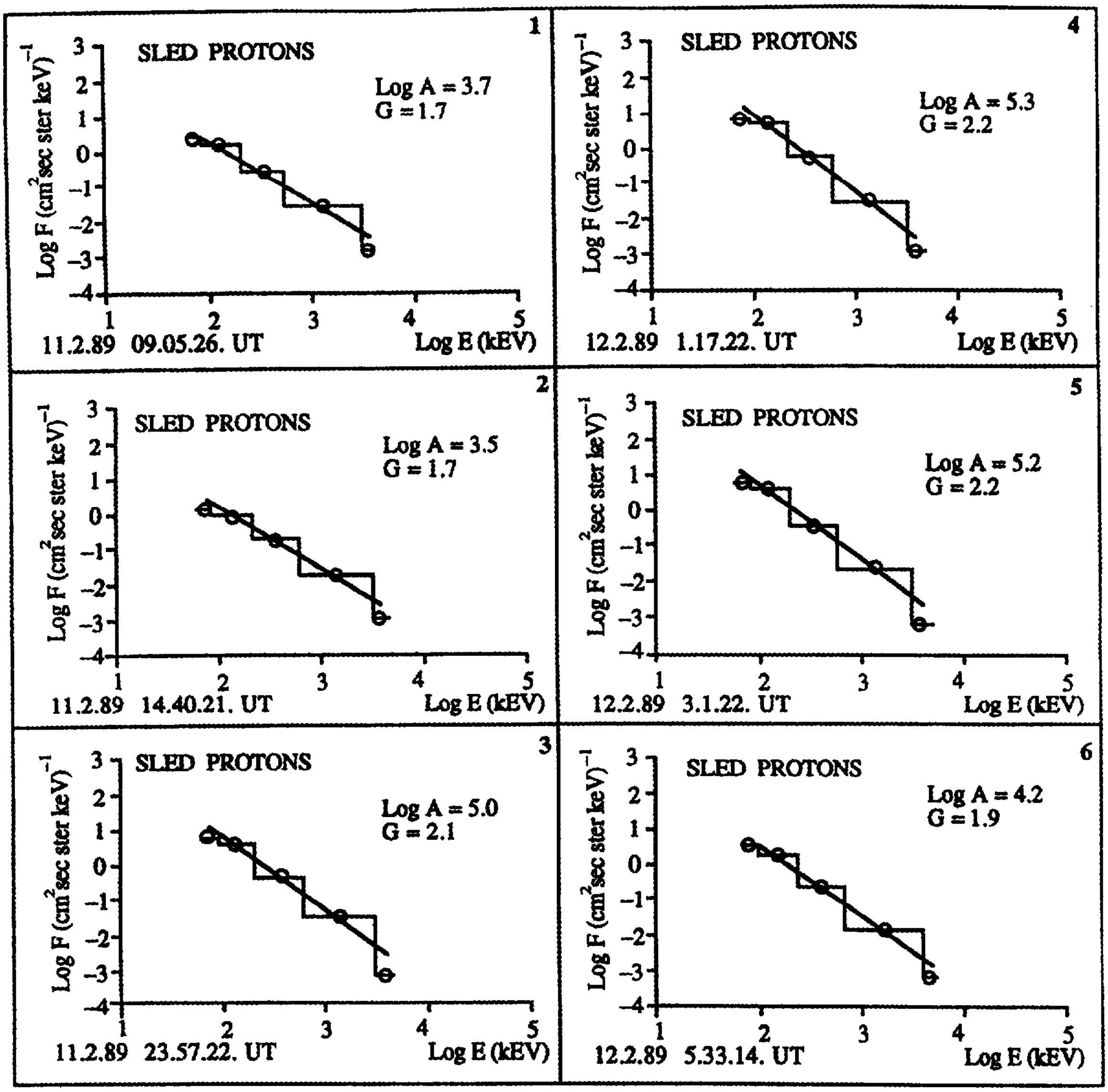

Fig. 12. Differential energy spectra recorded by SLED at various locations along the trajectory of Phobos-2 during Elliptical Orbit 4 on 11 and 12 February, 1989 (integration time 240 s). For details see Table 4. A fit to these data on the assumption of a power law $F = A \times E^{-G}$ is provided in each case

(1989) and by McKenna-Lawlor *et al.* (1992a), some of which, as a result of subsequent investigations, can now be neglected. Three competing mechanisms can still be advanced to explain the observations. Firstly, if Mars possesses a magnetosphere, the observed enhancements could represent a zone of trapped radiation, similar to the

Table 4. Details concerning differential energy spectra measured at various locations along the trajectory of Phobos-2 during Elliptical Orbit 4 which, see Fig. 12, were each fitted with a power law $A \times E^{-G}$

Plot	Date, 1989	(Time) U.T.	Log A	$(-)G$	Location
1	11 February	$09^h.05^m.26^s$	3.7	1.7	In the Solar Wind (inbound) during a declining background particle enhancement
2	11 February	$14^h.40^m.21^s$	3.5	1.7	While traversing the Planetosphere during a declining background particle enhancement
3	11 February	$23^h.57^m.22^s$	5.0	2.1	Within a representative maximum
4	12 February	$01^h.17^m.22^s$	5.3	2.2	Within a representative maximum
5	12 February	$03^h.01^m.22^s$	5.2	2.2	Within a representative maximum
6	12 February	$05^h.33^m.14^s$	4.2	1.9	In the Solar Wind (outbound) during ongoing background activity

Van Allen belt in the inner part of the magnetosphere of the Earth. Since, however, the gyroradius of the ions concerned is approximately equal to the height of the spacecraft above Mars, those particles of higher energy in such a population would be quickly lost through interacting with the dense Martian atmosphere and, overall, the process could be described as constituting quasi-trapping rather than trapping. The observation that, during Orbit 3, the position of maximum flux recorded in three stimulated channels of T1 shifted with time towards lower energies, with the largest flux appearing in the lowest energy channel, is in accord with the interpretation that the particles were at least quasi-trapped.

Secondly, again on the premise that Mars possesses a magnetosphere, sporadic merging of planetary with interplanetary magnetic field lines on the day side of the planet could lead to the acceleration of charged particles. These ions could then propagate along the boundary layer of the "magnetopause" from the day to the nightside of the planet, a process reported by Richter *et al.* (1979) to occur in the Earth's magnetosphere. In support of this possibility, it is noted that, at the part of the orbital trajectory concerned, SLED viewed directly along the surface of the "magnetopause" (see Fig. 1 which shows the "look direction" of SLED while in Elliptical Orbit).

Thirdly, the compression of magnetic field lines close to Mars reported by Riedler *et al.* (1989), which would be accompanied by an increase in density of the ambient plasma due to the piling up effect, could result in adiabatic acceleration of suprathermal particles to keV energies. A preliminary estimate by McKenna-Lawlor *et al.* (1993), based on MAGA observations of a magnetic field increase of the order of 10 G at the relevant location, indicates that, under the prevailing Solar Wind conditions, the increase in particle flux recorded should, as was observed, be approximately as great as the increase simultaneously recorded by the magnetometer.

Three-dimensional measurements made, over long dwell times, at low altitudes (down to ≈ 200 km) close to Mars, such as those proposed by McKenna-Lawlor *et al.* (1995) to be carried out during the Mars 96 Mission, are now urgently required in order to distinguish between these possibilities.

Energetic particles in the deep tail (recorded during circular orbit)

McKenna-Lawlor *et al.* (1993) reported the detection in the deep Martian tail of oxygen ions with energies ≥ 55 keV, travelling in beams along open field lines with, in some cases, a suggestion of confinement close to the neutral sheet. These observations may be compared with a report by Lundin *et al.* (1989) of the detection by ASPERA of beams of oxygen ions with energies of several keV, exiting the Martian tail. The associated loss rate of oxygen ions was estimated by these experimenters to be about 1 kg s^{-1}.

Lundin and Dubinin (1992) proposed that the beam-like acceleration of ionospheric ions observed in ASPERA data might result from an ion pickup process acting within spatially limited regions of the tail. The maximum energy thereby attainable was estimated to be 1 keV. An alternative mechanism for energizing the particles was suggested to be field aligned acceleration, similar to that taking place above the Earth's auroral oval. The latter acceleration process, which could produce ion beams with energies of just a few kiloelectronvolts, requires the presence of a static magnetic field. This explanation thus carries along with it the implication of the existence of a reasonably strong intrinsic magnetic field at Mars.

It was suggested by Kirsch *et al.* (1992), that the energetic ions recorded in the Martian Tail by SLED could have been impelled by reconnection events similar to those already reported by Sarris *et al.* (1976) to occur in the Geomagnetic Tail. Arguments advanced by Axford (1991), however indicate that, while a process such as magnetic field line reconnection can, indeed, be suggested to accelerate the observed particles (there is not enough time, for example, for a resonant process such as ion cyclotron wave acceleration to work satisfactorily within the required time scale), it is difficult to estimate precisely the energies particles can achieve as a consequence of being involved in a reconnection process. The placing of limits based on the magnetic energy per particle

$$B_t^2/8\pi n \ll mv^2/2 \ll (2\beta R_M/h)B_t^2/8\pi n$$

(where B_t is the magnetic induction in the tail; βR_M is its radius and h is the thickness of the plasma sheet) results, on taking values for the various parameters appropriate to the Martian environment, in predicted particle energies in the range 0.25–6.00 keV. The lower energy corresponds to the case where a particle displays the Alfven speed, while the upper value corresponds to the energy potentially available if the whole of the magnetic energy in the tail is converted into particle energy.

The 6 keV thus estimated is considerably lower than the value of ≥ 55 keV measured by the SLED instrument. However, as pointed out by Axford (1991) the influence of the Hall effect should have been included in the calculation in view of the large ion gyroradii (1600 km for an atomic oxygen ion in a 10 nT magnetic field) involved. Theoretical work in this regard is ongoing with a view to improving the model. Meanwhile, magnetic connection between captured interplanetary and intrinsic magnetic field lines on either side of the neutral sheet may be invoked as a candidate mechanism for accelerating energetic heavy ions down the Martian Tail. Detailed aspects of this process remain unclear and further, three-dimensional, *in situ* measurements are required to elucidate the phenomenon.

Particles at Mars associated with solar processes

At the time of the encounter of Phobos-2 with Mars, the interplanetary medium was, as already noted, undergoing a transition from solar minimum dominated to solar maximum dominated conditions. Energetic particles produced in association with phenomena characteristic of each of these phenomenological states (CIRs, "Impulsive" and "Gradual" Solar Events as defined by Reames, 1993; see also below), were in fact all recorded during the approximately two month period when the spacecraft was in orbit around Mars (McKenna-Lawlor *et al.*, 1991, 1992a; Marsden *et al.*, 1991).

Particles recorded in association with solar activity (i.e. events external to the planet), displayed significantly higher energies (several tens of MeV) than those associated with the locally accelerated particle populations described in the preceding sections (up to several hundred keV). The most energetic of these "external" events occurred at the end of the mission when a particle population associated with a "Gradual" SEP Event—in which particles are accelerated from the ambient plasma by the shock wave ahead of a Coronal Mass Ejection (CME) moving out through the heliosphere (Reames, 1993)—arrived at Mars. These particles, which stimulated all of the channels of SLED (see Table 1) and thus displayed energies >30 MeV, enveloped the planet from 9 to 26 March, 1989—when telemetry contact with the Phobos-2 spacecraft was lost (see Marsden *et al.*, 1991; McKenna-Lawlor *et al.*, 1991). This should be compared with the earlier "Gradual" shock-related SEP Event recorded from 7 to 15 February, 1989 which was characterized by energies up to ≈ 3.2 MeV (see Figs 8 and 9), and which displayed much lower fluxes.

A numerical model which includes particle injection at the Sun and at the shock front, and particle propagation through the interplanetary medium, has been developed by Heras *et al.* (1991) to describe acceleration at such CME driven shocks. (Particles associated with Impulsive Flares, on the other hand, have unusual ^{3}He-rich, Fe-rich abundances resulting from electron-beam-induced resonant wave–particle interactions in the associated flare plasma (Reames, 1993).) Most major particle events in the interplanetary medium are now recognized to be "Gradual Events" and the picture described above in which particles are accelerated (for a period of days) over an extended region of solar longitude in association with a CME driven shock, supersedes earlier models that, over a period of about thirty years, attempted to explain solar particle profiles in terms of slow diffusion across the corona and the interplanetary medium.

Conclusions

The close Martian environment is extremely dynamic and complex when viewed in energetic particles. Three localized populations of particles with energies compositely extending to several hundred keV, were discovered close to the planet in measurements made by the SLED instrument (at the Terminator Shock crossings; just inside the inbound Planetopause and travelling down the Tail).

Since the seed particles for ions accelerated at the Martian Bow Shock may be pre-accelerated solar particles, ions identified in SLED data at the Terminator Shocks over a two month period varied in energy between ≈ 50 keV (while Phobos-2 was in Circular Orbit) and ≈ 600 keV (during Elliptical Orbit 3).

Several mechanisms local to Mars have been considered to explain the energization of particles recorded close to the inbound Planetopause (≈ 225 keV) and travelling down the Martian Tail (≥ 55 keV). Three-dimensional studies made at low altitudes, ideally down to ≈ 200 km over long dwell times to monitor the influence of different interplanetary conditions, are now urgently required to allow a decision to be made as to which of the several candidate mechanisms considered are responsible for producing the observed effects.

Particles with energies up to several tens of MeV, which suffused the close planetary environment over extended periods, are interpreted to have been produced in solar processes external to Mars.

Particle enhancements at the Terminator Shocks provide topopgraphical information useful in modeling the Solar Wind interaction with the planet.

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