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ENERGETIC PARTICLE STUDIES AT MARS BY SLED ON PHOBOS 2

S. McKenna-Lawlor,* V. V. Afonin,** K. I. Gringauz,**
K. Kecskemety,*** E. Keppler,† E. Kirsch,† A. Richter,†
P. Rusznyak,* K. Schwingenschuh,‡ D. O'Sullivan,§
A. J. Somogyi,*** L. Szabo,*** A. Thompson,§ A. Varga,***
Ye. Yeroshenko‖ and M. Witte,†

** Space Technology Ireland, St Partick's College, Maynooth, Ireland*
*** Space Research Institute, Moscow, Russia*
**** Central Research Institute for Physics, Budapest, Hungary*
† Max Planck Institute fur Aeronomiem Germany
‡ Institut fur Weltraunforschung, Graz, Austria
§ Dublin Institute for Advanced Studies, Ireland
‖ Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Troitsk, Moscow Region, Russia

ABSTRACT

A preliminary overview of particle records obtained by the SLED instrument on Phobos 2, February-March, 1989 during Mars encounter, is presented. Data obtained while in close elliptical orbit around the planet (pericenter < 900 km), in both spin and three axis stabilised mode, display evidence of energy related particle shadowing by the body of Mars. This effect was also observed, under favourable conditions, in certain circular orbits (altitude 6330 km above the planet). Flux enhancements, inside the magnetopause, in the approximate range 30-350 keV, recorded in the same general location at < 900 km above Mars over an 8 day period during three consecutive elliptical orbits, are described. Possible explanations of these enhancements include the presence of quasi-trapped radiation at the planet and the detection of the propagation of accelerated particles along the boundary of the magnetopause from the day to the night side of Mars. Large anisotropic ion flux increases (1-1.5 orders of magnitude) in the approximate range 30-200 keV recorded in front of the bow shock (inbound and outbound) during certain circular orbits, provide evidence that the spacecraft traversed strongly anisotopic jets of energetic particles. These are suggested to have constituted O^+ ions. The pickup process would have been sufficient to accelerate such ions to their observed energies in the prevailing solar wind conditions. Alternatively, they might have comprised particles that had leaked from inside the magnetopause, perhaps undergoing shock drift acceleration in the process. Significant flux enhancements were also sometimes identified in the magnetotail (approximate energy range 30-50 keV). These are suggested to represent the signatures of O^+ beams, impelled by acceleration processes similar to those associated with terrestrial ion beams.

INTRODUCTION

The primary objectives of SLED were (a) to exploit the uniquely low perimartii (< 900 km) of the carrier Phobos spacecraft to mount a search for trapped particle populations close to Mars and (b) to seek for signatures indicative of interactions inside and outside a possible magnetospheric boundary layer enveloping the planet.

Originally, two spacecraft, Phobos 1 and Phobos 2, carrying identical SLED instruments, were launched from the Baikonur Cosmodrome on 7 and 12 July, 1988 respectively. Ground contact with Phobos 1 was lost at the end of August 1988. Phobos 2 meanwhile continued to transmit data to Earth and, after a 204 day flight, was transferred on 1 February 1989 into a series of highly eccentric orbits around Mars with a perimartian of approximately 860 km. The spacecraft was then transferred, first to an elliptical orbit of high pericenter, then to a circular equatorial orbit with an altitude of about 6330 km and finally, in March, to an orbit nearly synchronous with that of the Phobos Moon. Ground connection with the spacecraft was lost at the end of March. Data recorded by the SLED detector system while in the first four eliptical orbits, and also during 114 circular orbits, about Mars are presented and discussed.

METHODOLOGY

The SLED detector system comprised two semiconductor telescopes, each incorporating two silicon surface barrier detectors, mounted coaxially. The front detectors in each telescope used four discriminators, thus providing four separate energy thresholds. Single back detectors were used in each case to reject particles that penetrated the front detectors.

Through appropriate coincidence/anticoincidence arrangements, six different energy channels for each telescope could be defined, see Table.1 Count rate differences between the telescopes, (Te 1 and Te 2), which observed in the same direction but with open and foil covered apertures respectively, allowed protons and electrons to be distinguished, using a method due to Anderson et al. /2/. The detectors were at a temperature of < 10° C throughout the mission and a special heater was provided to switch on automatically if the platform temperature fell below the operating limit for the detectors. In Te 2, protons with energies < 350 keV, helium ions <1.6 MeV and oxygen ions < 8 MeV, as well as electrons < ~ 30 keV, were stopped in the foil (the absorber in front of Te 2 was composed of 500 μg cm^{-2} Al on mylar and the front detectors of both telescopes were covered by a 15 $\mu g\ cm^{-2}$ Al layer). Each telescope was, in addition, shielded by 5.6 g cm^{-2} Al and Ta to prevent protons with energies <70 MeV and electrons < 10 MeV from reaching the detectors.

TABLE 1 SLED Data Channels

Telescope without foil (Te 1)	Telescope with foil (Te2)
34-51 keV ions & electrons	38-51 keV electrons + 350-400 keV protons
51-202 keV ions & electrons	51-204 keV electrons +400-500 keV protons
202-609 keV ions & electrons	204-605 keV electrons + 0.5-1 MeV protons
0.6-3. 2 MeV ions	0.8-3.2 MeV ions
3.2 -4.5 MeV ions	3.2- 4.5 MeV ions
> 30 MeV (background rate)	> 30 MeV (background rate)

The geometric factor of each telescope was 0.21 cm^2 ster and the FOV axis, with a 40° apex angle, was in the ecliptic plane at 55° to the west of the sunward direction (the nominal direction of the interplanetary magnetic field at Mars). The time resolution was 230 sec. The SLED instrument is described in detail in McKenna-Lawlor et al. /3/.

MAGNETIC SHADOWING EFFECTS CLOSE TO MARS

At the time of the first eliptical orbit around Mars (1 February, 1989), the environment of the planet was greatly disturbed by the presence of particles of solar origin with energies up to a few MeV. Also, the spacecraft was operating in a spin, rather than in its usual three axis stabilised, mode (the rotation period about the sun-spacecraft-line = x axis varied in the range 440-700 sec. after orbit correction manoeuvers). Fig. 1 shows (panel 4 from top) particle counts recorded by SLED in Te 1, Channel 2 (51-202 keV) upper trace, and in Te 1, Channel 3 (202-609 keV) lower trace, from 17.38-19.55 U.T. on 1 Feburary, 1989. The upper two panels show the sun-spacecraft-line component of the magnetic field Bx and the magnetic field magnitude B, recorded, over the same period, by MAGMA on Phobos 2 with, below, the corresponding particle pitch angle of the SLED instrument. The last panel in the figure presents the calculated shadowing of the SLED aperture FOV in relative units, assuming a non spinning spacecraft.

The particle data presented in Fig. 1, show that, as the spinning spacecraft flew into the nightside of the planet, two deep minima occurred in the particle counts, two spacecraft rotations apart. A less deep minimum occurred in the intermediate position between these features. It can be inferred from the observations on 1 Feburary and on other dates (see for example Fig. 2 which shows a marked diminution in counts recorded on 8 Feburary and 11 Feburary when the spacecraft was similarly disposed to the planet but three axis stabilised) that, during this part of the orbit, screening of the aperture of the SLED instrument by the body of the planet was influenced by the pertaining magnetic field direction and by the pitch angle distribution of spiraling particles - an effect known as magnetic shadowing. Specifically, on 1 Feburary, the data indicate that, superposed on the spin related modulation of particle counts, specially depressed count rates were produced due to magnetic shadowing when the pitch angle remained relatively stable during the integration time of the instrument (see the pitch angle data referring to those deep minima located two spins apart). The less pronounced minimum recorded after one spacecraft spin marks a period when the associated pitch angle was showing rapid changes.

Signatures showing similar characteristics to those seen in Fig.1 (but not illustrated here) were recorded during elliptical orbit 1 in the particle data of Te 1, Ch. 1, and in Chs. 4-5 ; also during elliptical orbit 2 (when the spacecraft was still in spin-mode) in the data of Te 1, Chs. 3-5. The effect was further seen, during orbits 1-2, in Chs.1-5 of Te 2. The potential to produce reduced count rates, as described above, appears to have been counteracted in the data of Te 1, Chs. 1-2 (orbit 2) by the circumstance of the presence of particle enhancements at the relevant energies – see Fig.2 and a related discussion in the next major section.

Corresponding depressions in fluxes of about one order of magnitude were recorded in the data of Te 1 during elliptical orbits 3-4, which, as already indicated above, were executed under spin stabilised conditions, The effect is illustrated in the left hand panels 2-3 of Fig.2 for Channels' 1-3. Complementary count rate reductions are seen in the data of Te 1, Chs.3-5, left hand panel, Fig. 3, and in the data of orbit 4 for Te 1, Channels 3-5, right hand panel, Fig. 3. These flux reductions had well defined counterparts in the data of Te 2. The decreases observed were energy dependent in both telescopes.

Decreases in particle fluxes, attributed to magnetic shadowing, were in adddition recorded in approximately 20% of the circular orbits executed by Phobos-2 about Mars at an altitude of about 6000 km. The decreases in fluxes recorded were particularly marked when the ambient interplanetary medium was disturbed by solar flare activity, McKenna-Lawlor et al. /4, 5/. The fact that decreases in particle fluxes were only observed in a limited number of circular orbital revolutions appears to have been a consequence of spacecraft nutation.

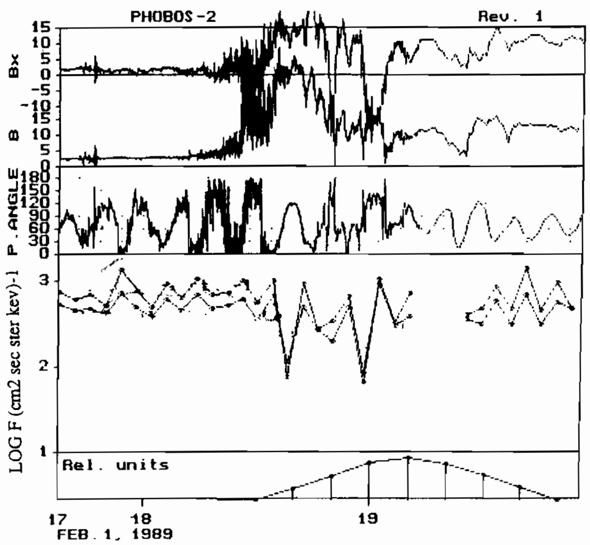

Fig.1. The two upper panels show, respectively, the sun-spacecraft-line component of the magnetic field Bx and the magnetic field magnitude B recorded by MAGMA on Phobos 2 during the first eliptical orbit around Mars, 1 February, 1989. The third panel shows the corresponding particle pitch angle of the SLED instrument. The fourth panel shows the concomitantly recorded flux of energetic ions recorded by SLED in Te 1, Ch. 2 (51-202 keV keV) upper trace and in Te 1, Ch.3 (202-609 keV) lower trace. The last panel shows the calculated degree of screening of the SLED aperture FOV by the planet body (arbitary units).

ENERGETIC PARTICLES IN THE MARTIAN ENVIRONMENT

Fig. 2 (left hand panel) shows data obtained during the relatively quiet interplanetary conditions characterising orbit 2 and during more disturbed ambient conditions while in orbits 3-4. Complementary drawings (right hand panel) show the individual spacecraft trajectories in cylindrical co-ordinates, the position, during each orbit, of pericentre (PC) as well as the locations, during orbits 2 and 3, of crossings of the bowshock (BS) and magetopause (MP) - information kindly provided by the cold plasma (TAUS) and magnetic field (MAGMA) experimenters.

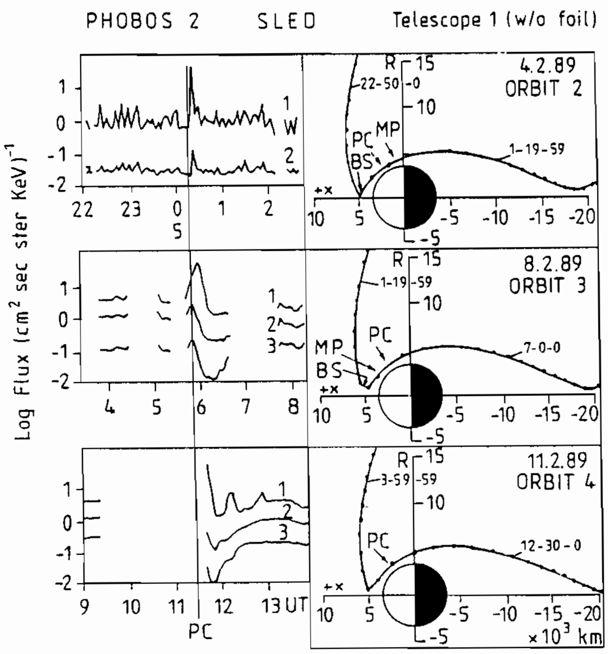

Fig.2. Particle fluxes (left hand panel) measured by SLED in Te 1. Ch. 1 (34-51 keV); Ch. 2 (51-202 keV) and, in two instances, in Ch. 3 (200-600 keV) during elliptical orbits 2, 3 and 4 on 4/5, 8 and 11 Feburary, 1989 respectively. The right hand panels show, for the same orbits, the radial distance R (in 1000 km) of the spacecraft from the x axis (Mars-Sun line) and the positions of the bow shock (BS), and the magnetopause (MP), as measured by the magnetic field and plasma experiments on Phobos 2.

The data show that, on 5 Feburary, just after the spacecraft crossed the magnetopause, a well defined enhancement in fluxes attaining a value of approximately two orders of magnitude and a duration of 8 minutes was recorded in Te 1, Ch1 when the spacecraft was approximately 900 km above the planet. A less pronounced peak of approximately one half an order of magnitude was associatively recorded in Ch. 2. No enhancement was observed in the foil telescope and the increases recorded in Te 1 appear to have been produced by protons in the approximate range 30-200 keV.

During orbit 3, particle fluxes also increased in Te 1, Chs.1-3 after the spacecraft crossed the magnetopause. The duration of the effect was approximately 26 minutes. The largest enhancement occurred in the lowest energy range. The peak of the enhancement in Chs. 2 and 3 occurred about 5 minutes earlier than that in Ch. 1. No special response was observed in Te 2.

In orbit 4 there was a telemetry gap when the spacecraft was approaching, and located at, pericentre but, from about 4 minutes thereafter, see Fig. 2, the declining phase of a flux enhancement was present in the data of Te 1, Ch. 1. The position of the boundary of the magnetopause is not known in this case. Again, no complementary enhancement was recorded in Te 2.

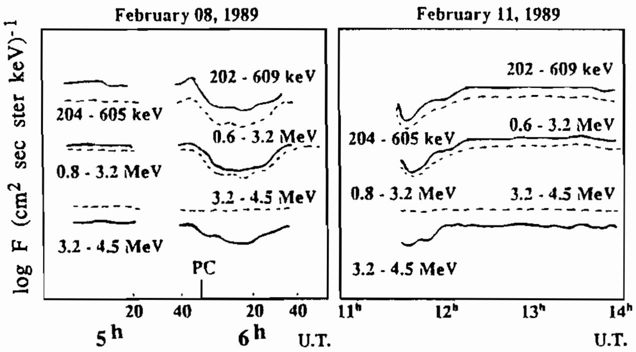

Fig.3. Particle fluxes (left hand panel) measured by SLED in Te 1 (solid line) and in Te 2 (dashed line), Chs. 3-5 on 8 Feburary, 1989; particle fluxes (right hand panel) measured by SLED in Te 1 (solid line) and in Te 2 (dashed line), Chs. 3-5 on 11 Feburary, 1989.

The fact that particle increases were recorded by Te 1 in the same general location (< 900 km) above the planet over about 8 days, suggests the stable existence inside the Martian magnetosphere of enhanced, possibly trapped radiation. The lack of unambiguous data concerning the structure of the ambient magnetic field militates against stating that the signatures recorded represent trapped ion radiation (< 34- < 350 keV) but does not exclude this possibility. Since however the gyroradius of a proton is approximately equal to the height of the spacecraft, such radiation could only be quasitrapped. Those particles with higher energies in such a population would be quickly lost since, due to their large gyroradii, they could interact with the dense atmospheric layers of Mars. The shift of the maximum of intensity to lower energies during the peaks recorded during orbit 3 may reflect this process (the delay in response between channels provides an indication that scattered light from the body of the planet was not the source of the observed enhancements, see a preliminary suggestion in Afonin et al. /8/).

Energetic particles might have been transported to the location where they were observed or, alternatively, an initially less energetic population in that environment might have undergone local acceleration. Sporadic merging of planetary with interplanetary magnetic field lines on the dayside of the planet could lead to an acceleration of charged particles which might then propagate along the boundary of the magnetopause from the day to the nightside of Mars, a phenomenon already observed in the Earth's magnetosphere, Richter et. al. /6/. Interestingly, at the part of the orbital trajectory concerned, SLED, in each case, viewed directly along the surface of the Martian magnetopause, parallel to the magnetic field direction, Afonin et al. /7/. Thus, this mechanism for providing a source for the energetic particles (< 34 -<350 keV) is an attractive one. Other possible explanations of the ion enhancements recorded are discussed in Afonin et al. /8/ and in Kirsch et al. /9/.

Since the statistical sample available for analysis (particle enhancements during 3 eliptical orbits) is so small, it will probably be ncessary to await the results to be provided by SLED-2 on the Mars-94 mission, (which is designed to make 4π steradian measurements over prolonged periods at an altitude of < 200 km above the planet), before the implications of the present SLED observations can be fully understood.

SHOCK ASSOCIATED ENERGETIC PARTICLES

In certain circular orbits, particle enhancements in the approximate energy range 30-200 keV, attaining 1-1.5 orders of magnitude and having a duration of about 1.5 hours, were recorded at the bow shock in Te 1 but not in Te 2. Examples of these intensity enhancements are shown in Fig.4, which presents particle fluxes recorded in the first four channels of Te 1 from approximately 03.00 U.T. 23 Feburary to 03.00 U.T. 24 February, 1989. During this interval the spacecraft was rotating (rotation period 11.8 m) and, since the FOV of the SLED aperture was only 40° full cone, the observed flux modulation is due to spacecraft spin.

A special study by Afonin et al. /10/ shows that there are no periodicities in the count rate increases that could be attributed to sunlight scattered from the planet.

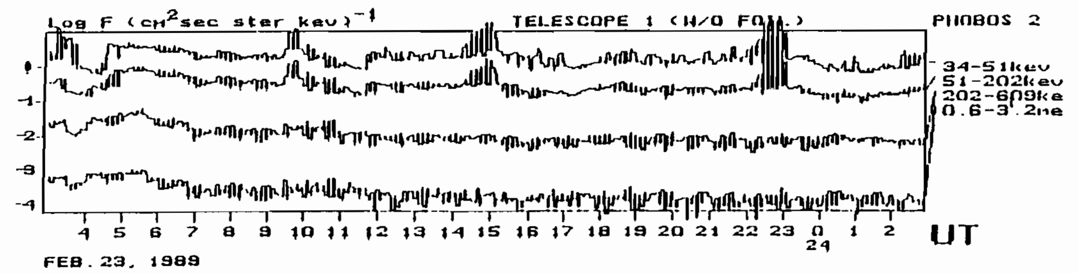

Fig.4. Particle fluxes in the first four channels of Te 1 over the interval 23 Feburary, 03.00 U.T.- 24 February, 03.00 U.T., 1989 when the spacecraft was in spin mode.

It is significant that the increases were typically observed just before or just after the bow shock as defined by the magnetic field data. Fig. 5 shows (top two panels), for a representative case, the spacecraft-sun-line component of the magnetic field Bx and the magnetic field magnitude B measured by MAGMA compared with (panel 3) the measured particle fluxes recorded simultaneously by SLED in Te 1 (34-51 keV) from approximately 14.00 -21.00 U.T. on 2 March, 1989. (Circular Rev. 42). The calculated shadowing of the SLED aperture field of view is presented in the next panel in relative units, assuming a non spinning spacecraft. The bottom display shows the time behaviour of the spectral index G, determined every 3m 50s, through fitting a power law ($F = A*E^{-G}$) to the first four steps of the spectrum using a least squares fitting technique.

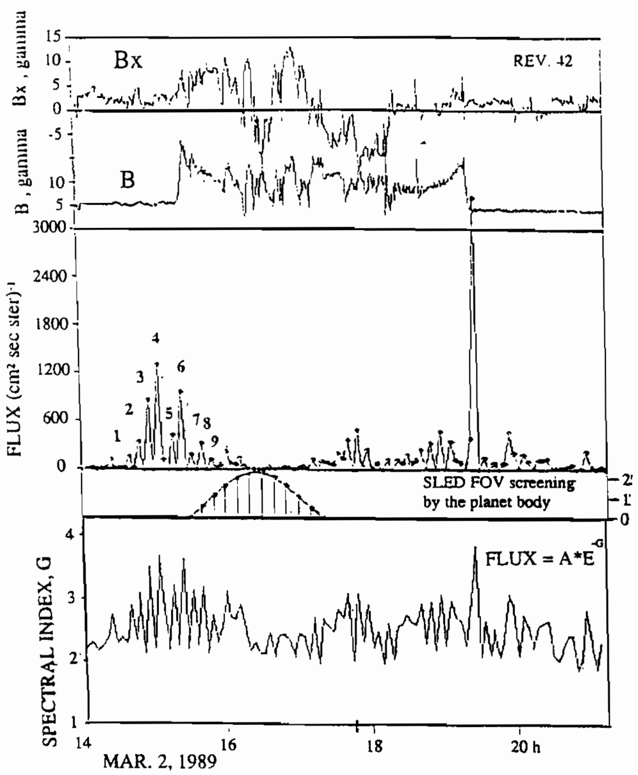

Fig.5. The top two panels show the sun-spacecraft-line component of the magnetic field Bx and the magnetic field magnitude B measured by the MAGMA instrument from approximately 14.00 U.T.-21.00 U.T. on 2 March 1989. Panel 3 shows particle fluxes measured by SLED in Te 1 Ch. 1 (34-51 keV). Panel 4 presents the calculated shadowing of the SLED aperture FOV in relative units assuming a non spinning spacecraft. Panel 5 provides temporal variations of the spectral index, calculated every 3m 50s, obtained by fitting a power law to the first four steps of each spectrum using a least squares fitting technique.

In Fig. 5, the position of the bow shock, inbound/outbound, is well defined by an abrupt measured increase/decrease in the magnitude of B. Spatially associated particle flux increases, inbound, occurred in a broad region in the undisturbed interplanetary medium, just before, and for some little time after, the spacecraft crossed the bow shock and entered the Martian magnetosphere. A particle spike was recorded just outside the bow shock as the spacecraft exited the magnetosphere. It is interesting to note that, on this day, minor particle intensity increases were also observed inside the magnetosphere itself. This latter phenomenon occurred relatively rarely during the 114 circular orbits traversed and the amplitudes of the increases observed were typically much lower than those recorded near the bow shock.

DIFFERENTIAL ENERGY SPECTRA

At the present early stage of the analysis, we cannot separate protons from electrons and therefore do not know how the data from the foil telescope should be plotted. Corrections for various background contributions have still to be made and the influence of electron fluxes on the shape of the spectra assessed. Nevertheless, the data of Te 1 allow us to make preliminary conclusions concerning the particles detected.

Figs. 6 presents a pair of differential energy spectra pertaining to Rev. 42. One is for the peak of the flux increases recorded in Te 1 in front of the bow shock (designated peak 4 in Fig. 5); the other is for the complementary particle background (labeled B). No corrresponding increase was recorded in Te 2. The background spectrum was calculated both outside and inside the flux increase region just immediately before the flux peaked due to spacecraft spin. The shaded area is the difference between the peak spectrum and the background spectrum. Fig. 7 presents a similar pair of spectra pertaining to the event recorded as the spacecraft traversed the bow shock outbound. The slopes of the differential energy spectra inside the observed maxima relative to background, coupled with the stability of the background spectra, suggest that a strongly anisotropic flux of particles was detected both inbound and outbound. These particles appeared in the SLED field of view streaming along the shock boundary.

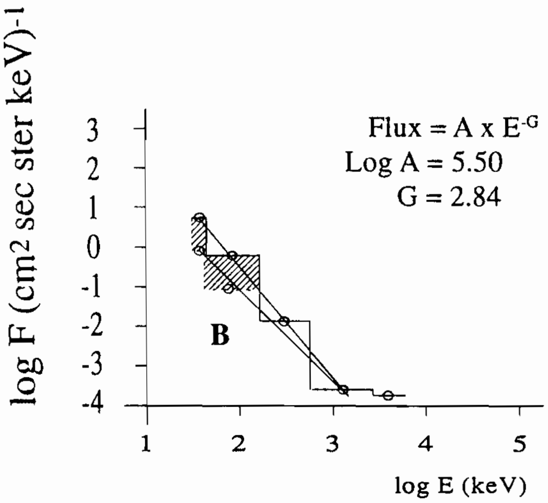

Fig.6. Differential energy spectrum of the flux increase labeled 4 in Fig. 5 and the corresponding background spectrum (B).The shaded area is the difference between the peak spectrum and the background spectrum.

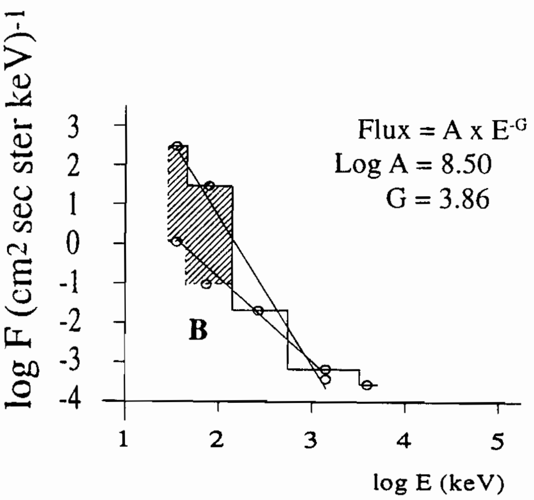

Fig.7. Differential energy spectrum of the flux increase recorded at the outbound bow shock (Rev. 42) and the corresponding background spectrum (B). The shaded area is the difference between the peak spectrum and the background spectrum.

Inbound, the anisotropic burst of ions was first detected at about 5000 km from the shock. Outbound, the peak was detected adjacent to the shock and it was about 1000 km wide. The ion enhancements observed upstream and downstream of the inbound bow shock and in the interplanetary medium beyond the outbound bow shock, all had energies in the range < 34 keV-~200 keV. Fig. 5 shows the time behaviour of the spectral index G for particles recorded in Te 1 during Rev. 42. A rise in G, with a high peak nearly ten minutes before the shock, a decrease, then another, slightly lower, peak at the shock itself can be identified, followed by a gradual decline in the post shock region. The behaviour of G inside the shock is characterised by more marked variations than those exhibited by the particle fluxes. The very high peak in flux recorded as the spacecraft exited the bow shock at 19.25 U.T. was associated with a short duration increase in G.

Fig. 8 shows how the slope of the differential energy spectrum varied within the spin modulated peaks upstream of the (inbound) shock, labeled 1-4 in Fig. 5. Peak 5 was associated with a time when Bx was a minimum and there was no longer a good connection with the spacecraft. The spectra associated with peaks 6-9, which were downstream from the, inbound, bow shock are plotted in Fig. 9. Spectral evolution across the shock can be followed through comparing the plots in Figs. 8 and 9.

Van Ness et al. /11/ distinguish four classes of shocks on the basis of the behaviour of their spectral indices. During Rev. 42, the inbound variation of G presented an irregular profile while outbound, a spike was observed. Both of these types of profile are deemed in /11/ to be associated with shock drift acceleration at quasi-perpendicular shocks.

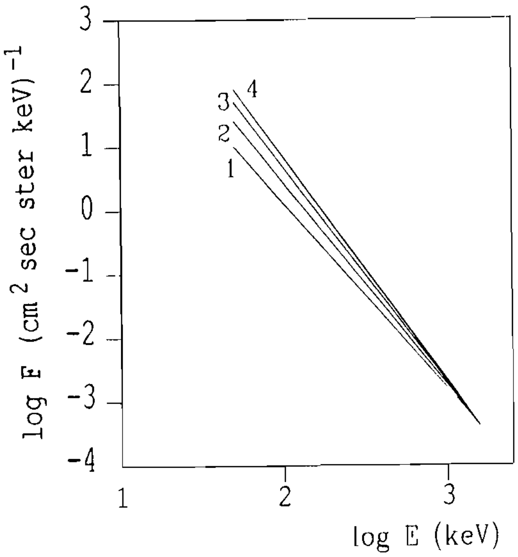

Fig.8. Differential energy spectra of the spin modulated peaks labeled 1-4 in Fig. 5.

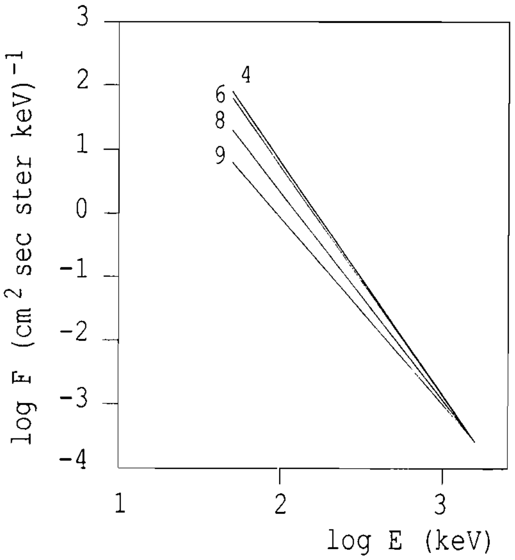

Fig.9. Differential energy spectra of the spin modulated peaks labeled 6-8 in Fig. 5.

Shock Drift Acceleration occurs 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 X B electric field (where v is the plasma bulk velocity and B is the magnetic field). The amount of energization depends on the number of times the particle crosses the shock and, in this connection, some authors combine the shock drift mechanism with first order Fermi acceleration to demonstrate that the particle can encounter the shock multiple times. As shown by Decker /12/, shock spike events can be produced through the single encounter shock drift acceleration of a charged particle at a quasi-perpendicular shock. In such a case, the existence of a high intensity spike in close temporal association with a shock can be explained as due to the kinematic accumulation of particles accelerated and transmitted downstream of that shock.

Studies by Krimigis /13/ of energetic ions upstream of various planetary bow shocks have led him to suggest that magnetospheres can constitute reservoirs of pre-accelerated ions from which, under appropriate conditions, energetic particles can escape into the upstream interplanetary medium and appear in the foreshock region. Such ions are likely to gain further acceleration by the shockdrift mechanism at the planetary bow shock before escaping.

Energetic particle populations identified, in particular, upstream of the earth's bow shock are generally divided into two main types, 'reflected' and 'diffuse'. see the review by Tsurutani and Rodriguez /14/. 'Reflected Ions' extend from solar wind energies up to only a few keV, with peak intensity generally at 4-5 keV and a steep decay beyond. They are highly anisotopic and, in the frame of the solar wind, stream along the magnetic field away from the bow shock. The source of these particles has been theoretically explained as a gradient B drift of solar wind ions along the quasi-perpendicular shock surface in the direction of the interplanetary v_{SW} X B electric field. Diffuse Ions, on the other hand, extend from solar wind energies up to 100-200 keV. Beyond about 30 keV they exhibit differential intensity spectra that are exponential in energy and they are approximately isotropic in the frame of the spacecraft near the bow shock. Several sources have been suggested as the origin of these ions, including disruption and acceleration of reflected ion beams by wave particle interactions; solar wind acceleration in the quasi-parallel bow shock and leakage of magnetospheric ions. An intermediate state between the reflected and diffuse populations is also recognised and it is suggested by some authors that reflected particles are the source of this diffuse population, thus indicating an upstream origin of diffuse ions rather than a bow shock origin.

In the light of the above, we may speculate if the energetic ions recorded upstream of the Martian bow shock could be part of a diffuse population accelerated at the bow shock. At the earth, an excellent correlation exists between diffuse ions and low frequency (0.01-1 Hz) MHD and ion-accoustic like plasma waves and, in this connection, it is interesting that the Plasma Wave System (PWS) on Phobos-2 detected, in the shock foot, broad band noise extending from below the lower hybrid frequency to the electron-plasma frequency, Grad et al. /15/. However, as pointed out by Ip /16/ diffuse bow shock acceleration is limited by the dimension of the system concerned and, since the Martian bow shock is much smaller that that of the Earth, it is reasonable to infer that diffuse ions would not be accelerated at Mars by this process to energies up to 200 keV. Also, the process is most effective for quasi-parallel shocks and, as shown by Schwingenschuh et al /17/, the inbound shock at Mars was quasi-perpendicular.

Leakage of pre-accelerated particles from inside the magnetopause constitutes an attractive possibility to explain the ions recorded by SLED, and of course such particles could undergo further acceleration by the shock drift mechanism before escaping into the upstream medium. Interestingly, the SLED instrument has already provided evidence of the presence, inside the magnetopause, of particles with energies in the range <34- <350 keV (see above). See also the observation of Kirsch et al. /9/, noted in the next section, which indicates that energetic ions were detected at > 50,000 km upstream of the bow shock.

ION IDENTIFICATION

Pre-launch calibrations indicate that, in order for oxygen ions to be recorded in Te 1, Channel 1 of SLED, they should have energies in the range 55-72 keV; in the case of Te 1, Channel 2, the required energy range would be 72-223 keV. See also Keppler /18/. According to Nagy and Cravens /19/, the main source of hot oxygen ions (0.8-0.96 eV) at Mars is from the dissociative recombination of O_2^+ ions and it has been shown by Afonin et al /10/, that, at the height of the Phobos spacecraft (approximately 6000 km), the corresponding hot oxygen density, 10 ions/cm^3, would be sufficient to produce the energetic particle flux increases observed during circular orbit.

The ion pick-up process generates a maximum energy of $E_{max} = 2M.V^2 \sin^2\alpha$ (where M = ion mass; V = solar wind velocity and α = angle between the solar wind and magnetic field direction). For a typical solar wind speed of 400 km/s, a proton can gain only 4 keV in energy (maximum) from this process. An O^+ ion, however, can gain 64 keV and an O_2^+ ion 128 keV so that these ions should be detectable in Te 1, Channels 1-2 of SLED. In the eliptical orbits close to the planet traversed by Phobos 2, the pick-up process, acting alone, at the pertaining solar wind speed would thus have been sufficient to accelerate oxygen ions to such energies.

Measurements obtained by the MAGMA instrument aboard Phobos indicate that the magnetic field upstream of the Martian bowshock (and the shock foot) was initially about 2.7 nT. An 80 keV oxygen ion in a 3 nT field has a gyroradius of 54,000 km so that pickup ions detected by channels 1-2 of SLED should have their origin > 50,000 km upstream. In this connection it is interesting that Kirsch et al /9/ have identified particle enhancements which they interpret to be due to O^+ ions at distances up to 17 Martian radii from the planet.

Copious fluxes of oxygen ions with energies in the ranges 0.5-25 keV/q and 0.01-6 keV/q have been observed in the Martian magnetotail by the ASPERA experimenters, Lundin et al. /20/. A plot, Fig. 10, showing fluxes of H^+ and O^+ ions in the energy range 10-23 keV from 14.30 U.T. -20.30 U.T. on March 2, 1989, reproduced here through courtesy of the ASPERA experimenters, shows that the dominant flux from near the bow shock crossing (inbound) to the bowshock crossing (outbound) was due to oxygen ions. This observation appears to provide support for the interpretation that the flux enhancements recorded by SLED were due to O+ ions.

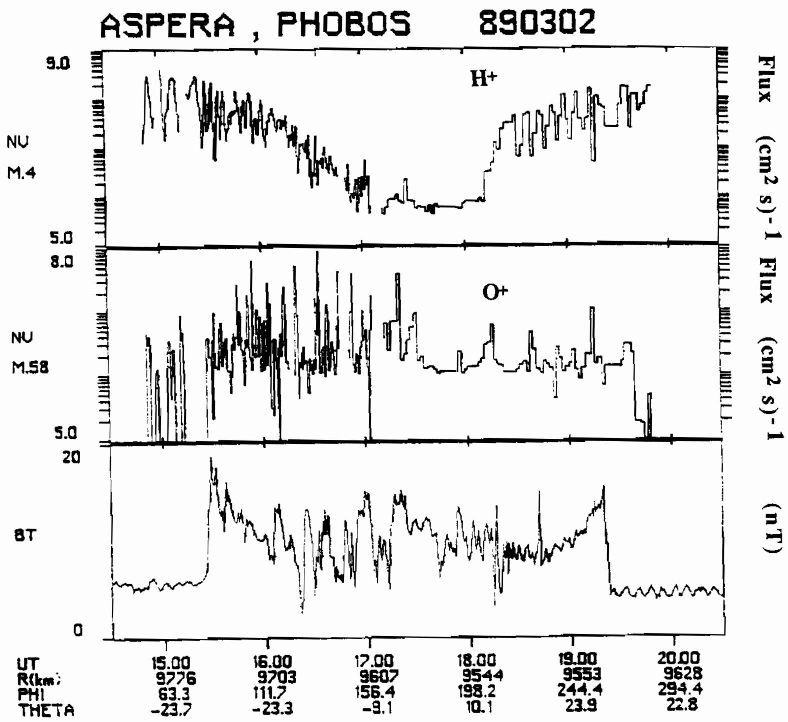

Fig.10. Fluxes of H^+ and O^+ ions recorded in circular orbit at Mars on 2 March, 1989 by the ASPERA instrument aboard the Phobos spacecraft, compared with the magnetic field magnitude B, concomitantly recorded by the MAGMA instrument.

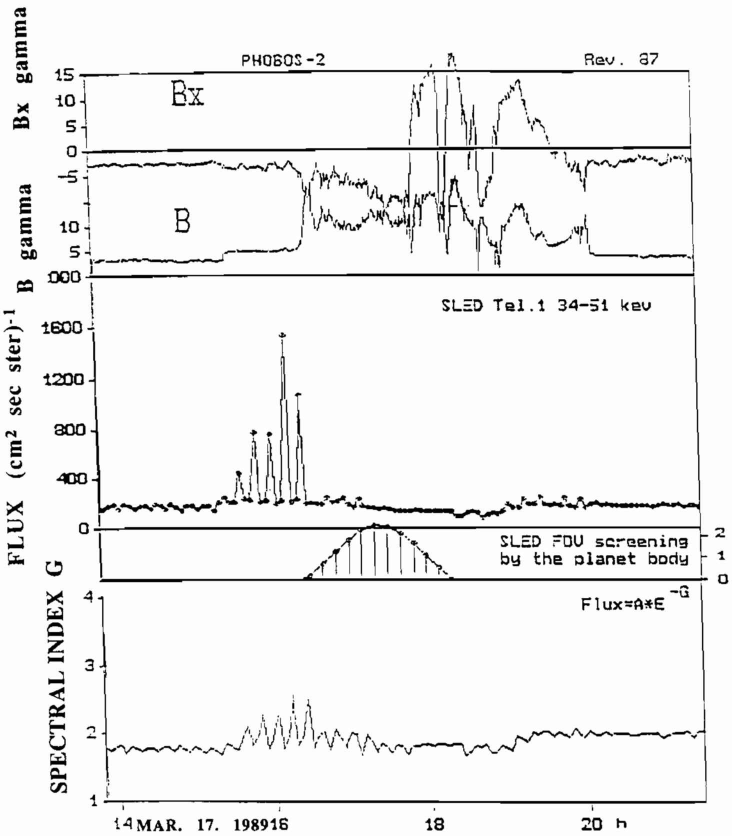

Fig.11. See the analogous caption of Fig. 5.

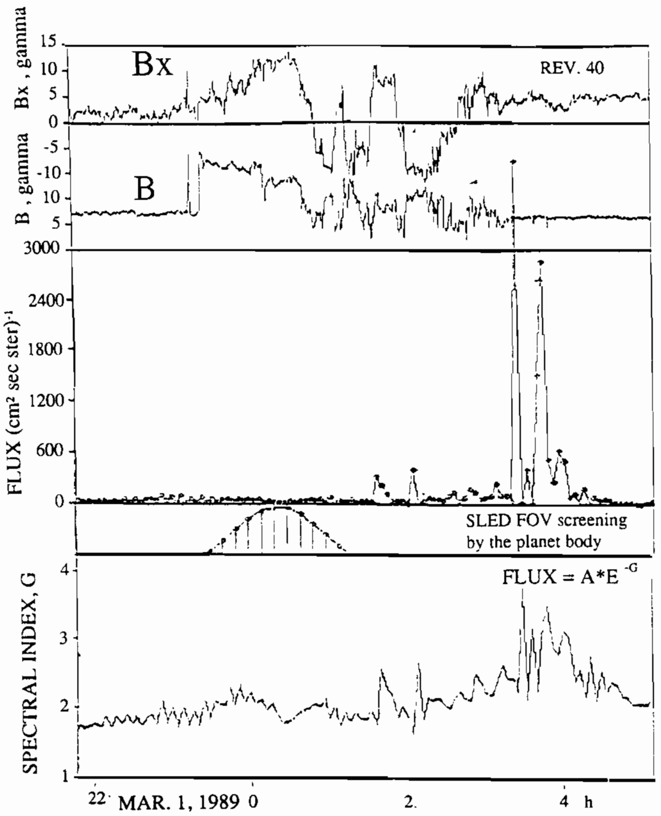

Fig.12. See the analogous caption of Fig. 5.

OTHER ENERGETIC PARTICLE EVENTS

The event of 2 March, 1989 represents only one of an extensive sample of energetic particle events recorded by the SLED instrument while in 114 circular orbits about Mars. Some of these records show bow shock associated flux increases only when the spacecraft was inbound (see Fig. 11). Others show bow shock associated flux increases only when the spacecraft was outbound (see Fig. 12). Others show flux increases both inbound and outbound (see Fig. 5) and some show no flux increases at all at the bow shock. At the present time a detailed study is in train in an effort to identify the circumstances (such as the background level of disturbance of the Martian environment due to solar activity; the nutation of the spacecraft etc.) accompanying each kind of record.

TAIL EVENTS

Of particular interest are the minor flux enhancements which, in a limited number of cases (see, for example Fig. 5), were recorded in the magnetotail by Te 1, Ch. 1 (energy range 34-51 keV) which it is here suggested may correspond to O^+ beams escaping from the ionosphere impelled by acceleration processes similar to those associated with auroral ion beams in the earth's magnetosphere. See the complementary report by Lundin et al. /20/ of O^+ beams with energies up to several keV recorded in the central tail by the ASPERA instrument.

CONCLUSION

In close eliptical orbit, energy related particle shadowing by the body of Mars was detected. This effect was also detected, under favourable conditions, when in circular orbit approximately 6000 km above the planet. Also, significant particle fluxes in the approximate range 30-<350 keV were detected inside the magnetopause in the same general location, at <900 km above the planet, over 8 days. Possible explanations of these latter enhancements include the presence of quasitrapped radiation at Mars and the detection of the propagation of accelerated particles along the boundary of the magnetopause from the day to the night side of the planet.

In circular orbit, many significant flux enhancement events in the approximate energy range 30-200 keV were detected adjacent to the bow shock. The particles concerned are suggested to have constituted O^+ ions. The pickup process would have been sufficient, under prevailing solar wind conditions, to accelerate such ions to their observed energies. Alternatively, these ions might have leaked upstream from inside the magnetopause, perhaps undergoing shockdrift acceleration at the bow shock in the process. Minor flux enhancements in the magnetotail in the approximate energy range 30-50 keV are suggested to constitute the signatures of O^+ ions, impelled by acceleration processes similar to those associated with terrestrial auroral ion beams.

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