ENERGETIC PARTICLES (>34 KeV - 3.2 MeV) IN THE DEEP MARTIAN MAGNETOTAIL (X = 15.5 R_M),MODELING OF THE MARTIAN BOW SHOCK AND THE INFLUENCE OF LOW SOLAR WIND PRESSURE ON MARS AS AN OBSTACLE

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ABSTRACT

The first observations of energetic particles (range > 34 keV - < 3.2 MeV) in the tailward part of the Martian magnetosheath as well as during crossings of the Martian Bow Shock within the deep magnetotail (X = 15.5 R_M), are reported, using data from the SLED instrument on Phobos 2. The energies observed cannot be attained by the pickup process acting alone. Sporadic field line merging at the dayside of the planet could conceivably accelerate the particles to the observed energies. The presence of an unusually weak dynamic solar wind pressure during orbits 3 and 4 suggests that a weak intrinsic field could have expanded outwards under these conditions to provide a dayside obstacle radius for Mars of up to about 2000 km.

1. INTRODUCTION

The Phobos 2 spacecraft to Mars and its Moons was launched from the Baikonur Cosmodrom on 12 July, 1989. After a Cruise Phase to Mars of 204 days, it was commanded on 1 February, 1989 into a series of four highly eccentric orbits about Mars (period approximately 79 hours, pericenter approximately 860 km). On 12 February, it was raised to an elliptical orbit of high pericenter (period approximately 86.7 hours, pericenter approximately 6,407 km), following which it was transferred into a series of 114 circular orbits at a height above the planet of 6145 km.

In the present paper, energetic particle observations obtained by the onboard energetic particle detector SLED during two of the 'close' eliptical orbits (orbit 3 which commenced on February 8, and orbit 4 which commenced on February 11) are examined to find evidence of Bow Shock Crossings in the deep tail region of Mars. The data obtained during orbits 1 and 2 cannot be utilized in the present study since, during orbit 1, the Martian environment was greatly disturbed by solar related activity and, during orbit 2, the SLED instrument was switched off due to spacecraft manoeuvres while Phobos 2 was flying in the deep tail.

2. THE SLED INSTRUMENT

SLED utilized semiconductor detectors in two telescopes (Te 1, Te 2) directed at 55 ° to the spacecraft sunline. This line of sight direction agrees approximately with the direction of the nominal interplanetary magnetic field at Mars. The geometric factor of each telescope was 0.21 cm^2 ster with a 40 ° opening angle. The first detector of Te 1 was covered with 15 υg/cm^2 aluminium and recorded both ions and electrons. Te 2 was covered with an additional foil which absorbed protons with energies less than 350 keV but allowed the detection of 35-350 keV electrons.

Table 1

Channel	Energy Range			
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		
4	0.6-3.2 MeV	p		
5	3.2-4.5 MeV	p		
6	> 30 MeV	background rate		

Table 1 lists the energy channels of Te 1 of SLED for ions and electrons. The data of Te 2 are not used in the present paper. It is noted that Channels 1 and 2 could also respond to oxygen ions with energies of 55-72 keV and 72-223 keV respectively.The time resolution was 230 s. For a detailed account of the instrument see Ref. 1.

3. ENERGETIC PARTICLE OBSERVATIONS

Data recorded by SLED in Te 1 (Channels 1-6) during close eliptical orbits 3 and 4 are described, for convenience, in reverse order. Orbit 4 commenced at 11.10 U.T. on February 11, 1989. Pericenter was passed at 11.30 U.T.. The data obtained along the orbit trajectory is incomplete, see Fig. 1, due to the switching off of the instrument during spacecraft manoeuvres. The enhancements recorded from approximately 11.34 - 15.00 U.T. are the subject of a separate study, (Ref. 2). Smooth fluxes were recorded from approximately 18.30 U.T. while the spacecraft was flying inside the magnetosphere. At approximately 19.45 U.T. (designated by the letters MP on the figure) we interpret the data to indicate that Phobos 2 crossed the Magnetopause and entered what is called at the Earth the Magnetosheath. Note the varying fluxes in four channels and the synchronism displayed between the flux variations in different energy regimes. A sharp drop in fluxes occured at approximately 03.45 UT as the spacecraft crossed the Bow Shock (marked B S) on February 12 and entered the undisturbed solar wind.

During Orbit 3, the spacecraft passed pericenter at 05.52 U.T. on February 8. Again, due to the switching off of SLED during

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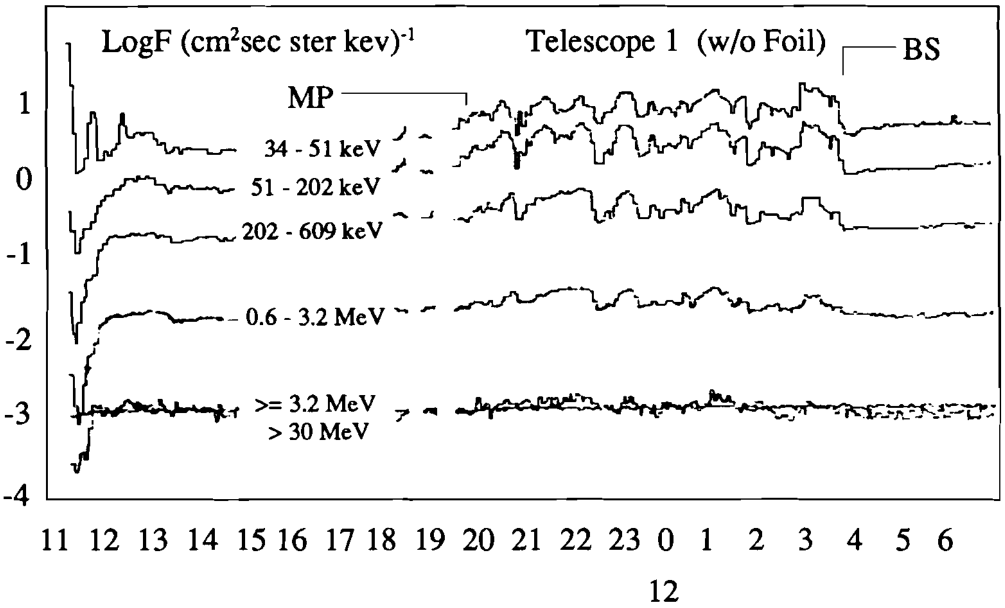

Fig. 1 *Particle fluxes recorded by SLED on Phobos 2 in Te 1, Channels 1-6 during the elliptical orbit of Mars from 11.30 U.T. on 11th February, 1989. The locations of the Magnetopause (MP) and Bow Shock (BS) crossimgs are specially indicated.*

manoeuvres, the data obtained along the spacecraft trajectory are incomplete, see Fig. 2. The particle enhancements observed near pericenter are the subject of a separate study (Ref. 2). Due to the fragmentary nature of the data obtained during this orbit, we cannot identify the location of the Magnetopause. However, the pattern of synchronously varying fluxes recorded in four channels within the Magnetosheath is similar to that recorded during Orbit 4 except that the variations are superimposed on a generally increasing rise in the flux level recorded in each channel.

Two significant jumps (down and up) are seen at 16.50 U.T. and at 17.15 U.T. respectively. These events coincide with a double bow shock crossing identified by Slavin et al. 1991 (Ref. 3) in the Phobos magnetometer (MAGMA) data. After 17.40 U.T. there was a gap in the energetic particle data.

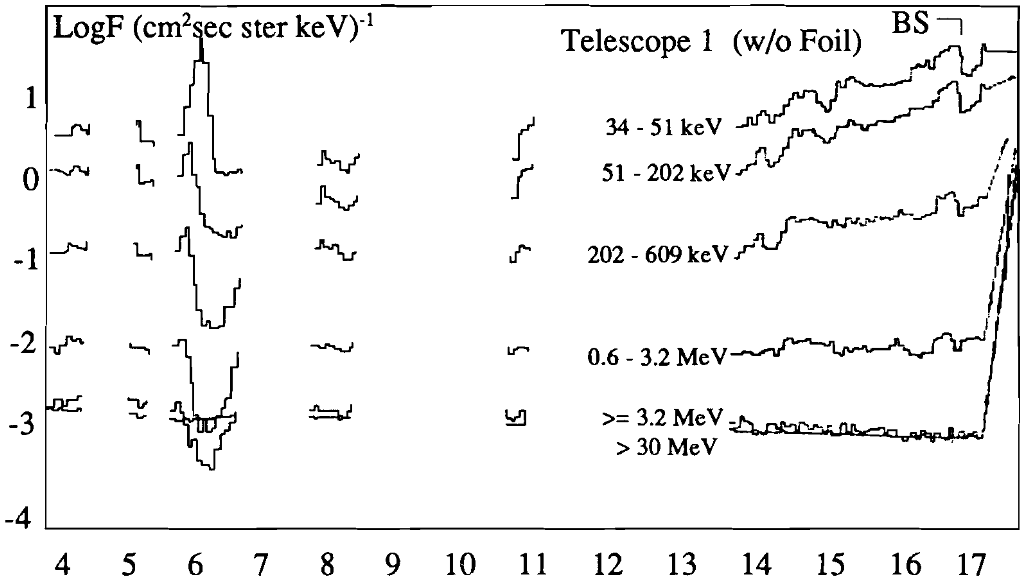

Fig. 2 *Particle fluxes recorded by SLED on Phobos 2 in Te 1, Channels 1-6 during elliptical orbit 3 of Mars on 8th February, 1989 from 04.00 U.T. - 17.30 U.T..*

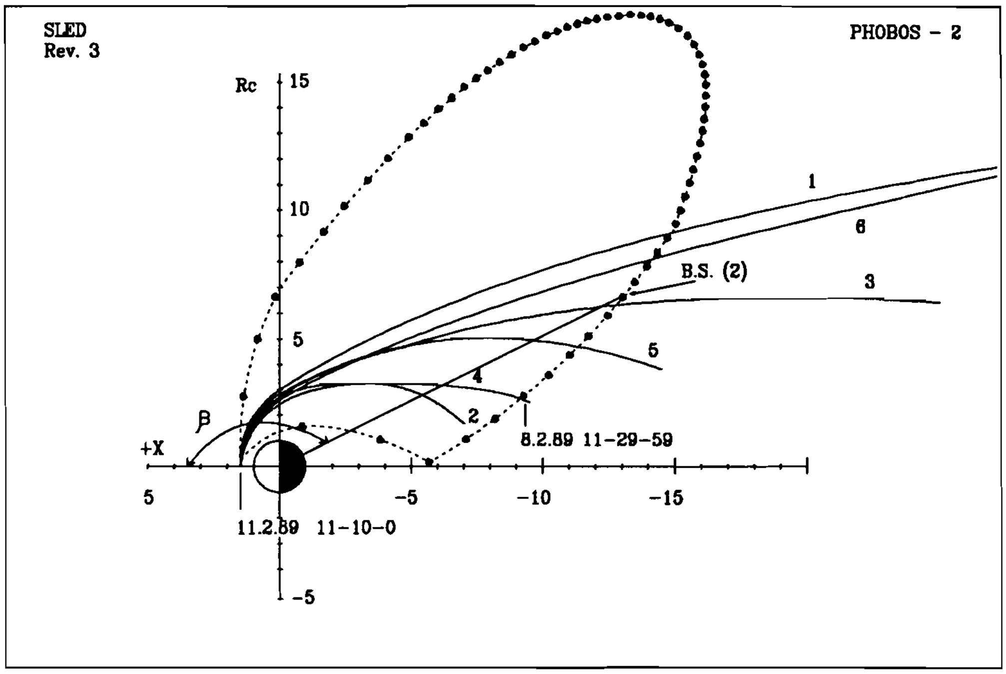

Fig. 3 *Plot in cylindrical MSO co-ordinates of elliptical orbit 3 of Phobos 2 about Mars on 8th February 1989, with timing marks shown every 60 minutes. Six models of the Martian distant Bow Shock position based on the parameters and observations listed in Table 2 are overlaid on this plot. The measured location of the Bow Shock (B.S.) crossing derived from SLED energetic particle data is indicated.*

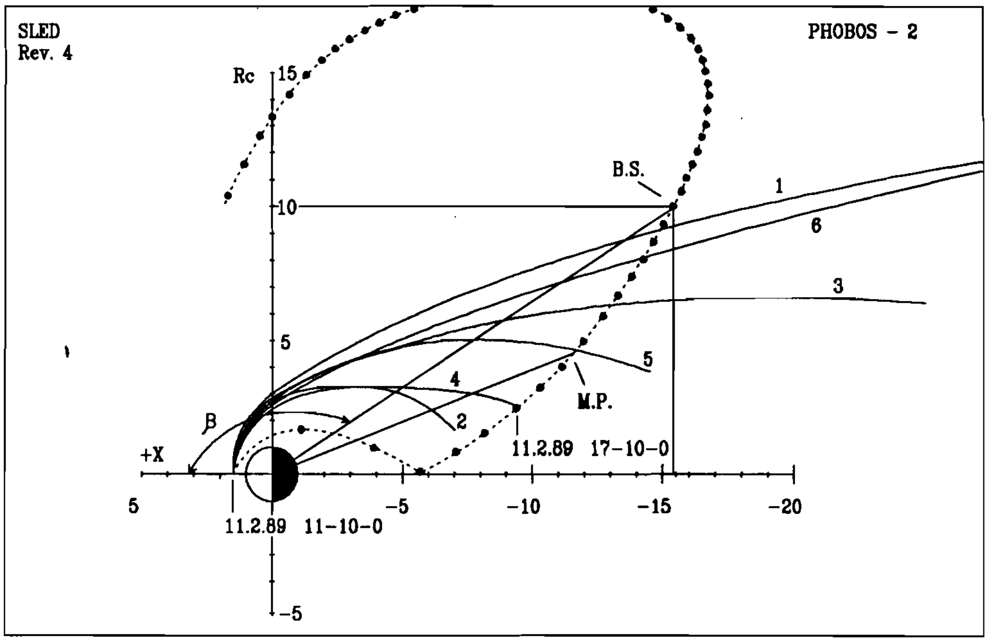

Fig. 4 *Plot in cylindrical MSO co-ordinates of elliptical orbit 4 of Phobos 2 about Mars on 11-12th February, 1989, with timing marks shown every 60 minutes. Six models of the Martian distant Bow Shock position based on the parameters and observations listed in Table 2 are overlaid on this plot. The measured locations of the Magnetopause (MP) and Bow Shock (B.S.) crossings derived from SLED energetic particle data are indicated.*

4. ORBITAL PLOTS AND BOW SHOCK MODELLING

Plots of the Phobos 2 orbits 3 and 4 about Mars are presented in Figs. 3 and 4 respectively in cylindrical co-ordinates. The frame of reference used is the Mars centered solar orbital system (MSO) in which the X axis is taken to be positive towards the Sun, while Z is deemed to be normal to the plane of the orbit of Mars, with the positive direction to northwards. In each case, the vertical axis graphs distance from the X axis. In Fig. 4, the configuration of the upper right bend in the spacecraft trajectory indicates the change over to a second type of elliptical orbit on February 12.

For the purpose of modelling the shape and location of the Martian Bow Shock, the approach of Slavin and Holzer (Ref.3) and references therein is adopted. According to this procedure, the shock is represented as a conic section whose focus is allowed to move along the X axis until a best fit to the experimental data is found. Expressed in polar co-ordinates with respect to a focus located at X =0 (where aberation is neglected) the equation for the shock surface is

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

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

Six bow shock models constructed using this approach were found in the literature, Refs. (4-8) fitted, see Table 2, to individual and aggregate data sets based on various kinds of bow shock crossing observations taken aboard Mariner 4, Mars 2, 3 and 5 and Phobos 2. These models have been reconstructed for the present study using the parameters listed in Table 2 (which show some minor differences from those adopted in the original publications). The plots thus obtained are presented in Figs. 3 and 4 overlaid on the trajectories followed by Phobos 2 in orbits 3 and 4 respectively.

Table 2

Model	Ref.	S/C	Number Crossings	e	L (R_{Mars})	? Xo (R_{Mars})
1	4	Mars 2,3,5	11	0.99	3.00	0.0
2	5	Phobos 2	26	0.65	2.66	0.0
3	5	Phobos 2	26	0.95	2.17	0.5
4	6	Mars 2,3,5	14	0.94	1.94	0.5
5	7	Phobos 2	100	0.85	2.72	0.0
6	8 ?	Mariner 4 Mars 2,3,5 Phobos 2*	118	1.02	2.04	0.55

* Magnetometer and Plasma Wave System data

5. DISCUSSION (ENERGETIC PARTICLE DATA)

A double event marks the Bow Shock Crossing in the deep tail on February 8. On February 11, the data indicate that a single Bow Shock crossing was made. These are the first observations made in energetic particles (> 34 keV to at least 0.6 MeV and to less than 3.2 MeV) to provide information on Martian magnetotail topology .

In the magnetosheath, rapidly varying fluxes are visible in the data provided by energetic particles (also in the range > 34 keV to < 3.2 MeV). It is possible that the variations observed, which are not time differentiated between the different energy channels stimulated, represent directional changes. Detailed comparisons with magnetic data should be made to establish this point. At the present time it can, however, be stated that particles with energies up to 0.6 MeV are influenced by processes taking place in the Martian magnetosheath.

As is well known, the maximum energy attainable by the pickup process is given by the expression

$$E_{Max} = 2 M v^2 \sin^2 \alpha \qquad (2)$$

where M = ion mass; v is the solar wind velocity and α is the angle between the solar wind and the magnetic field direction.

The solar wind as measured by the TAUS experiment was 500-700 km/s in February and March 1989. Table 3 shows the maximum energies attainable by several ions at these solar wind speeds.

Table 3

v km/s	H+ keV	O+ keV	O2+ keV	CO2+ keV
500	5.25	100	200	275
700	12.25	196	392	539

Heavy ions stimulate the channels of SLED Te 1 (refer to Table 1). However, see Tables 1 and 3, the recorded particle energies (up to at least 600 keV) cannot be explained by the pickup process acting alone. The interaction of a Martian magnetosphere with the interplanetary magnetized medium could possibly lead to a local and sporadic merging of planetary with interplanetary magnetic field lines at the front side of the planet resulting, like at the Earth, in the acceleration of charged particles which could then propagate along the magnetosheath boundary from the day to the nightside (as already observed in the case of the Earth's magnetosphere, Ref. 8) In such a case, energetic particle enhancements recorded by SLED close to pericenter in orbits 3 and 4 when the instrument viewed directly along the surface of the magnetosheath (Ref. 9) might constitute a record, obtained close to the planet, of another segment of that surface encountered in the deep tail.

Identification of the mechanism/s accelerating the particles recorded in both locations will be the subject of a later study.

6. DISCUSSION (BOW SHOCK MODELS)

Of the various models (1-6 of Table 2) illustrated in Figs. 3 and 4, Models 3 and 6 provide, when compared with the SLED data, the best predictions of the locations of deep tail bow shock crossings. Model 3 was based on 26 bow shock crossings recorded by the Plasma Wave System (PWS) on Phobos 2 whereas Model 6 was based on an aggregate sample of 118 crossings assembled from various spacecraft flying a variety of sensors.

While considerable latitude remains for varying the parameters employed in predicting bow shock crossings at large distances, it appears from the SLED data that the value adopted for the eccentricity of the bow shock should be of the order of 1.00 in order to achieve successful modelling.

Table 4

Boundary Crossing	Rev.	X km	B* deg.	pv^2 dynes/cm^2
Bow Shock	3	-12.9	152.8	0.3
Bow Shock	4	-15.2	148.2	0.2
Magnetopause	4	-11.6	158.3	

* Sun-Mars-Spacecraft Angle

Consideration of the SLED data indicates, see Table 4, that the distant Bow Shock locations identified during revolutions 3 and 4 were $X = -12.9\ R_M$ and $X = -15.2\ R_M$ respectively. It is noted that, in Ref. 3, the value of X at the distant bowshock crossing made during orbit 3 by Phobos 2 was derived from the magnetometer (MAGMA) record to be $-15.5\ R_M$. These data indicate that, at the prevailing solar wind speed in February (obtained from TAUS data), a solar wind dynamic pressure of approximately $0.2- 0.3 \times 10^{-8}$ dynes cm^{-2} prevailed during orbits 3 and 4. The mean solar wind pressure at 1.5 A.U. is, however,predicted (Ref.3) to be in the range $0.8- 1.0 \times 10^{-8}$ dynes cm^{-2}.

Assuming the Mars magnetic moment to be 1.4×10^{22} G cm^3, values of the solar wind dynamic pressure for obstacle altitudes of 500, 2000 and 4000 km have already been individually calculated in Ref. 3 to be 1.5×10^{-8}, 0.22×10^{-8} and 1.5×10^{-8} dynes cm^{-2} respectively. Comparing these values with the situation pertaining on February 8 and on February 12, it appears that a weak intrinsic magnetic field could have expanded outwards on these days to provide a dayside obstacle radius for Mars of up to about 2000 km. Records of unusually distant dayside bow shock crossings noted in Ref. 3 to be present on various occasions in the Mars 2 and 3 as well as in Phobos magnetometer data, are in accord with this interpretation.

6. SUMMARY

Energetic particles (> 32 keV - < 3.2 MeV) were recorded by the SLED instrument on Phobos 2 in the tailward part of the Martian magnetosheath and at crossings of the distant bow shock (X =15.5 Rm). It is reasonable, on the basis of the observations, to infer that a weak intrinsic magnetic field could, under the conditions of low solar wind pressure pertaining during the taking of these observations, have expanded to provide a subsolar obstacle radius for Mars of up to 2000 km.

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