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Signatures of the Martian moon Phobos in the fluxes of energetic particles as measured by experiment SLED onboard *Phobos* 2

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Abstract. Energetic particles ($E_p > 34$ keV, $E_{0+} > 55$ keV), plasma ions (30 eV–6 keV) and magnetic fields have been observed onboard *Phobos* 2 during the approach phases of the spacecraft to the Phobos moon in February/March 1989. Water ions and protons escaping as neutral water molecules from Phobos and the Martian tail can generally be accelerated by the pickup process. The present study is concerned with the acceleration of particles at the evening side ($\alpha_{S/C} = 90°$) of the Martian bowshock, which escaped as neutrals, especially from the tail or at the front side of Phobos. Since the interplanetary magnetic field forms quasiperpendicular and quasiparallel shocks with the Martian bowshock, the shock drift and the Fermi acceleration process were considered as processes for a further acceleration. The observed particle fluxes are interpreted as protons of 34–200 keV and O^+ ions of 55–225 keV energy.

Introduction

After ≈200 days cruise phase, the *Phobos* 2 spacecraft (S/C) reached planet Mars on 31 January 1989 and performed first four elliptical orbits (pericentre 867 km, apocentre ~83.550 km) and, from 20 February 1989 onward, circular orbits ≈300 km above the Martian moon Phobos. Every 7 days the S/C approached Phobos to a distance of a few hundred kilometers on the tailward side. On 21 March 1989, a synchronous orbit was entered. The S/C was now always in front of the Phobos moon with respect to the Sun at a distance of 200–300 km. During the circular orbits, energetic particles were measured by the SLED experiment (Solar Low Energy Detector, McKenna Lawlor *et al.*, 1990), solar wind protons by the TAUS experiment (Toroidal Analyser Spectrometer, Rosenbauer *et al.*, 1989) and magnetic fields by the MAGMA detector (Riedler *et al.*, 1989), in the tail and in front of the Mars moon Phobos.

Bogdanov (1981) reported the first plasma observations obtained onboard the *Mars*-5 mission in the wake of the moon Deimos which showed a diameter of ≈5000 km 20,000 km behind the moon. Dubinin *et al.* (1990) found indirect evidence for a gas and dust torus along the Phobos orbit. In further papers, Dubinin *et al.* (1991a,b) studied the plasma and magnetic field effects of the Phobos and Deimos tails. They found cavities in the magnetic field, and draping of the field lines around the moons, indicating a comet-like behavior. The gas production rate of Phobos ($Q \approx 10^{23}$ mol s^{-1}) is, however, smaller by a factor of 10^7 than that of comet Halley (Dubinin *et al.*, 1991a).

Recent model calculations concerning the oxygen corona of Mars have been published by Ip (1990) and for the gas and dust emission of Phobos and Deimos by Ip and Banaszkiewicz (1990). The authors concluded that Phobos and Deimos are most likely to emit water vapor. From their Fig. 2 it can be derived that the gas ring has an extension of ≈ ±1000 km across the Phobos orbit. As soon as the gas becomes ionized, the water ions will be picked up by the solar wind and spread over larger distances. Thus, on the tailward side of Phobos, pickup ions and further accelerated ions can be expected.

It is the purpose of this paper to study the possible influence of the Phobos gas emission on the energetic particle fluxes ($E_p > 34$ keV, $E_{0+} > 55$ keV). As additional information, solar wind measurements by the TAUS experiment and magnetic field recordings by the MAGMA experiment were available. It is, however,

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Table 1. Energy channels of SLED, Te 1

Ch 1	34–51 keV p	55–72 keV O
Ch 2	51–202 keV p	72–223 keV O
Ch 3	202–609 keV p	225–630 keV O
Ch 4	0.6–3.2 MeV p	
Ch 5	3.2–4.5 MeV p	
Ch 6	>30 MeV p	

p = Protons, O = Oxygen

necessary to distinguish between solar particles, pickup ions from planet Mars (Kirsch *et al.*, 1991) and the expected effects of Phobos on the energetic particle fluxes.

Experiment description

The SLED instrument (McKenna Lawlor *et al.*, 1990) uses semiconductor detectors covered in the first telescope Te 1 by a 15 μg cm^{-2} foil and in the second telescope Te 2 by a 500 μg cm^{-2} aluminum foil. The thicker aluminum layer absorbs protons <350 keV, but allows the detection of 35–350 keV electrons. Only measurements of the first (open) telescope will be shown here. The energy thresholds of Te 1 for protons and oxygen ions are presented in Table 1.

The two SLED telescopes viewed at 55° to the S/C–Sun line. The opening angle of the telescope apertures was ±20°, the geometric factor 0.25 cm^2 ster and the time resolution about 240 s. Under normal conditions the *Phobos* 2 S/C was three-axis stabilized with the X-axis pointing to the Sun, but, after certain orbit correction maneuvers, it was slowly rotating at variables rates (440–700 s periods) around the S/C–Sun line (X-axis).

Observations

For the proposed study, particle and magnetic field measurements are investigated at times when the S/C approached the Martian moon Phobos. The orbits of the *Phobos* S/C and the Phobos moon were available and some approach phases could be selected. During the first two elliptical orbits, measurements in the Phobos tail were performed. However, the effects in the particles' fluxes and plasma data are only small and extend over somewhat different time intervals as determined by the encounter geometry. A clear identification of particles escaping from Phobos alone is therefore not possible for the elliptical orbits. The circular orbits (20 February–20 March 1989) also allowed measurements to be made in the tail of Phobos outside and inside of the Martian magnetosphere. During the synchronous orbits (20–26 March 1989) recordings in front of Phobos were obtained.

1. *Circular orbits*

The positions of the S/C and Phobos moon can be seen in Fig. 1 (first and second diagram). Owing to the different orbit periods of the S/C (~300 km above Phobos) and Phobos moon, the S/C approached the moon every ~7 days. Only two such phases which have the best data coverage will be shown here, whereby SLED obtained data in the tail of Phobos. Figure 2a demonstrates the second approach phase (26–27 February) during three-axis stabilization of the S/C. SLED data, B_x and B_{total} are shown. The B_z component (not shown) is ≈3.5–7 nT. TAUS measurements are not available. Increases in the SLED data were detected on both days near $\alpha_{S/C} \approx 90°$ (α = azimuth angle of the S/C orbit) and slightly inside

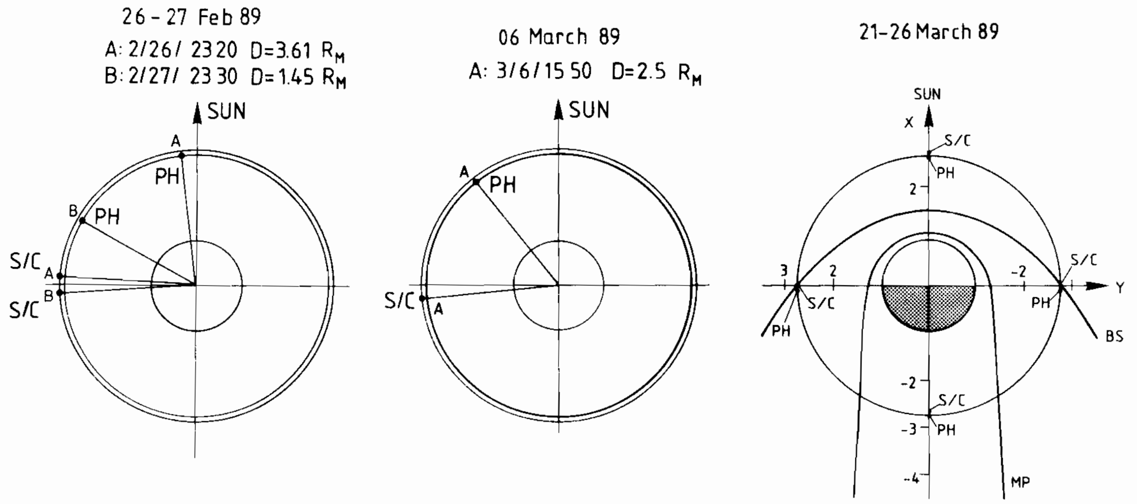
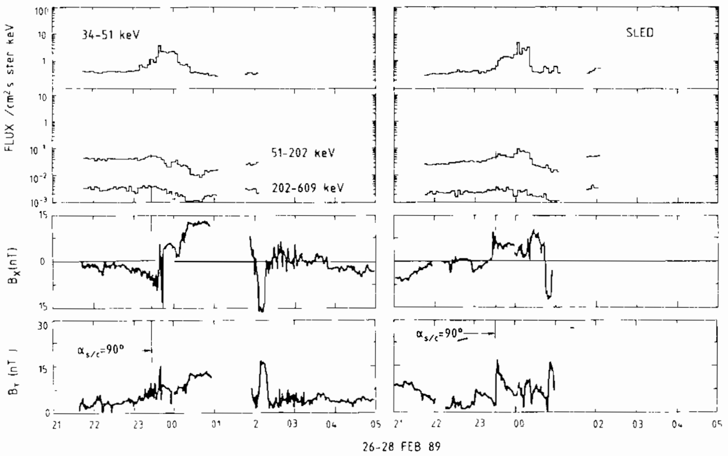
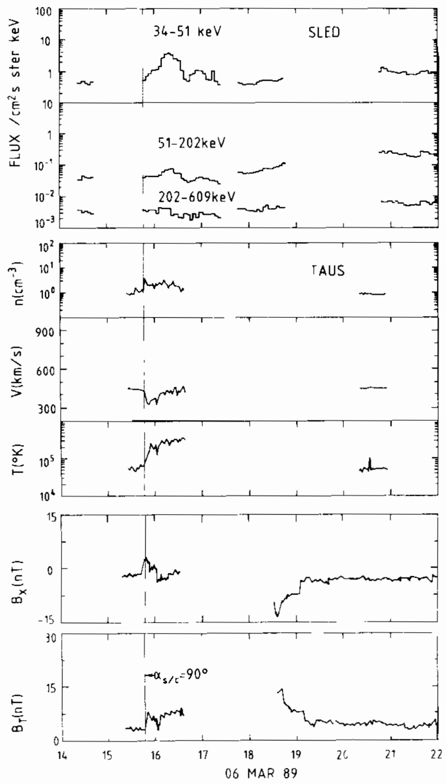


Fig. 1. Positions of S/C and Phobos during circular (Fig. 2a, b) and synchronous orbits (Fig. 3a, b). D = distance between S/C and Phobos in Mars radii for the positions A, B. During synchronous orbits (21–26 March 1989) the S/C was always in front of Phobos. The third diagram (21–26 March 1989) shows also the nominal position of the Martian bowshock (BS) and magnetopause (MP). Experiment SLED is looking at an angle of 55° to the S/C–Sun line



(a)



(b)

Fig. 2a, b. Second and third S/C–Phobos approach phases at the evening side of the Mars bowshock (compare Fig. 1). SLED data were observed slightly inside the tail (see B_{total}) during three-axis stabilization of the S/C. The TAUS experiment shows at the same time an increase of the plasma temperature (Fig. 2b)

the Martian bowshock. The distance between the S/C and Phobos was $D = 3.61 R_M$ (Mars radii) and $D = 1.45 R_M$ on 26 and 27 February, respectively (see Fig. 1). Anisotropy measurements which could help to distinguish between different acceleration processes are not available from the SLED experiment. The B_x component indicates that the neutral sheet of the Martian magnetosphere was crossed during polarity changes. The total field vector (not shown) was directed 45°–80° northward and ~180°–315° in azimuthal direction during the flux increases.

In Fig. 2b, the third approach phase is depicted which again shows a flux increase (6 March, 16:00–17:00 U.T.) slightly inside the Martian tail. The distance to the Phobos moon was $2.5 R_M$ (see Fig. 1). The S/C was three-axis stabilized on 6 March. The B_x component changed from negative to positive values, again indicating a crossing of

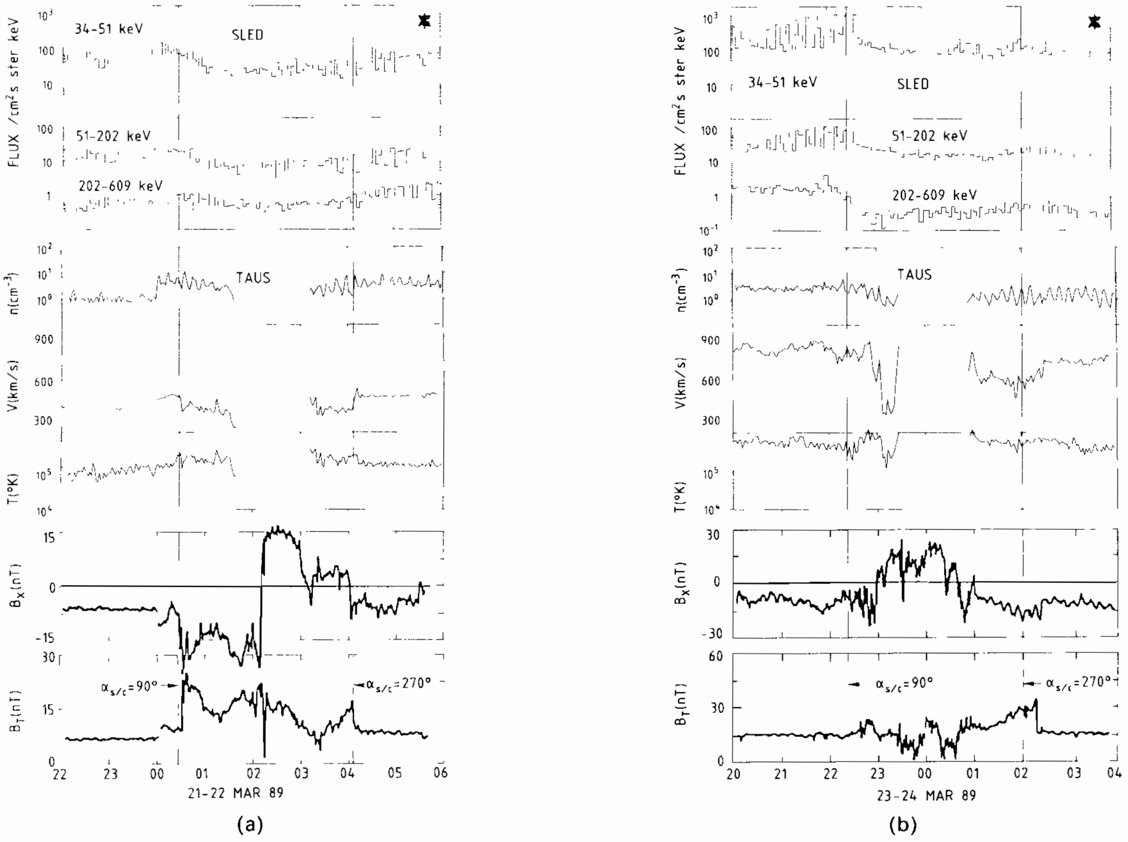


Fig. 3a, b. Two examples of particle flux increases during synchronous orbits together with TAUS and magnetic field measurements. The S/C was always in front of Phobos (compare Fig. 1)

the neutral sheet during the observation of the spikes, whereas B_z (not shown) varied between 3.5 and 7 nT. The elevation angle of the field vector (not shown) was 30 – 80 northward and the azimuthal angle between 200 and 315 . The TAUS data (Fig. 2b) indicate a simultaneous increase in velocity and temperature of the plasma after the bowshock of Mars was crossed.

The examples shown in Fig. 2 demonstrated that particle energies up to ≈ 200 keV were reached and that the intensity time profiles are similar. Planet Mars obviously has a shielding effect which terminates the observation of the spikes (compare Afonin *et al.*, 1991).

2. *Synchronous orbits*

From 21 to 26 March, the *Phobos* 2 S/C was orbiting always in front of Phobos at a distance of 200–300 km (Fig. 1). Intensity increases up to $E \approx 200$ keV were observed by SLED (Fig. 3a, b) when the S/C had an azimuth angle $\alpha_{S/C} \approx 90$. The S/C was rotating around the X-axis during the time intervals shown in Fig. 3a, b. Smaller increases also appeared near $\alpha_{S/C} \approx 270$, but less frequently.

The particle increases near $\alpha_{S/C} \approx 90$ start before the Martian tail is entered. The B_x component is negative during the whole particle flux enhancement (Fig. 3a, b). The TAUS plasma data show a density and velocity increase associated with the particle flux enhancements (Fig. 3a).

The second example (Fig. 3b) is generally associated with a high-speed solar wind stream of ~ 800 km s^{-1}.

Summary of observations

(1) The S/C approached the Phobos tail every 7 days during circular orbits. Spikes at the evening side ($\alpha_{S/C} \approx 90$) could then be detected by SLED at and slightly inside the Martian bowshock.

(2) Similar spikes were observed during synchronous orbits at the front side of Phobos when the S/C was again at $\alpha_{S/C} \approx 90$. Some spikes appeared also during periods with $\alpha_{S/C} \approx 270$.

(3) The magnetic field vector was inclined 45 -80 northward and the azimuthal angle was simultaneously 180 -315 during the examples shown in Fig. 2a, b, whereas B_z varied between 3.5 and 7 nT. During synchronous orbits (Fig. 3a, b) flux increases were observed outside and inside of the Martian tail, as B_{total} showed.

(4) The TAUS experiment measured outside of the Mars tail solar wind protons (density, velocity, temperature) and indicated the presence of high-speed solar wind streams and also sometimes acceleration processes at the bowshock by temperature, velocity and density increases.

Discussion

Ion acceleration at the morning and evening side of the Martian bowshock have already been studied by Afonin *et al.* (1991). The accelerated particles stem most likely from the Martian ionosphere and tail, since the examples were not especially selected for approach phases to the Phobos moon. However, one example presented by Afonin *et al.* (1991, Fig. 5) was identified in the present study (Fig. 2a, right-hand side) as an approach phase to Phobos. The observed spike was interpreted by Afonin *et al.* as a jet of energetic particles. Particle acceleration processes such as shock drift and the diffusive acceleration process were considered as the reason for the spikes and shall be studied here also.

The observed spikes at the Mars bowshock appear to be similar to spikes observed already at the Earth bowshock (Anderson, 1981; Tsurutani and Rodriguez, 1981; Scholer, 1985).

Ip and Banaszkiewicz (1990) have shown (their Fig. 2) that at the position of the Phobos moon the O^+ density due to emission from the Martian ionosphere is ≈ 200 O^+ cm^{-3}, while the Phobos outgassing (10^{23} mol s^{-1} total emission rate) produces in the center of the Phobos torus a density of 3000 O^+ cm^{-3}. It can be assumed that the larger plasma density in the Phobos torus correlates with higher fluxes of energetic particles measured by SLED. However, an acceleration mechanism is required which generates ion energies $E_p > 34$ keV, $E_{0+} > 55$ keV. Oxygen ions, resulting from the Phobos H_2O emission, can be picked up by the convection electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ of the solar wind. The maximum corresponding energy is given by:

$$E_K = 2MV^2 \sin^2 \vartheta,$$

where B is the interplanetary magnetic field strength, M is the mass of the particles, V is the solar wind velocity, ϑ is the angle between the solar wind and the magnetic field direction, and E_K is the kinetic energy of pickup ions.

The ion pickup process generates maximum particle energies for $\vartheta = 90$ and $\vartheta = 270$ and can be neglected for $\phi_{MAG} = 0$ or 180 because then $\vartheta \approx 0$. The maximum energies which a proton and an oxygen ion can gain in a solar wind stream of 400 km s^{-1} by the pickup process are 3.32 keV and 53.1 keV, respectively. A solar wind stream of 800 km s^{-1} as observed on 23–24 March 1989 generates 13.28 keV protons and 212 keV oxygen ions. Thus, only oxygen ions would be detectable by SLED when the pickup process is the only operating acceleration process.

For angles $\phi_{MAG} \simeq 45$ or 315, however, the interplanetary magnetic field is tangent to the bowshock and forms a quasi-perpendicular shock similar to the foreshock region at the Earth bowshock (Anderson, 1981; Gosling and Robson, 1985) because then $\Theta_{BN} > 45°$ (angle between direction of $\mathbf{B}$ and the normal to the shockfront). The field vector of the examples shown in Fig. 2a, b had an elevation angle of 45°–80°. It can be assumed that a quasi-perpendicular shock at the flanks of the bowshock and a more quasi-parallel shock ($\Theta_{BN} < 45°$) at the front side were formed and the shock drift as well as the diffusive acceleration process were realized. Therefore both acceleration processes shall be discussed as the reason for the spikes shown in Figs 2 and 3.

Flux enhancements could be observed when the S/C was simultaneously at $\alpha_{SC} \approx 90$, i.e. in the tail or in front of the Phobos moon. The particles then gain energy by drifting through the $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ electric field associated with the shock front (Chen and Armstrong, 1973; Armstrong *et al.*, 1985; Krimigis and Sarris, 1985; Gosling and Robson, 1985).

For the high-speed solar wind stream, the electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ or $E_y = -V_x B_z$ (Armstrong *et al.*, 1985) can be calculated for $V_X \approx 800$ km s^{-1}, $B_Z \approx 5$ nT, as $E_y \approx 4$ mV m^{-1}.

Thus, a field of ≈ 3–4 mV m^{-1} can be expected along the shockfront.

Assuming for the Martian bowshock a diameter of $5R_M \approx 16{,}965$ km and an effective acceleration length of $\approx 10{,}000$ km we find for proton and O^+ ions an energy gain of:

$$E_K = 4 \times 10^{-3} \frac{V}{m} \cdot 10^7 \,\mathrm{m} = 40\,\mathrm{keV}$$

and of 80 keV for O^{2+}.

Protons of 40 keV energy are detectable with channel 1 of SLED. Singly charged oxygen ions would only be detectable when they start already with an initial energy of a few tens of keV, resulting from the pickup process. The ions can also be reflected by the shock and re-encounter the acceleration region. The Fermi acceleration process (Axford *et al.*, 1977; Scholer, 1985) is realized when the interplanetary magnetic field forms a quasi-parallel shock ($\Theta_{BN} < 45$) with the bowshock of Mars. Multiple interactions of protons and oxygen ions lead then to energies of ≤ 300 keV (compare Krimigis and Sarris, 1985) which are detectable by SLED.

Since no anisotropy measurements were performed by the SLED experiment, it cannot be decided which of the two described acceleration processes is mainly responsible for the spikes observed at the Martian bowshock.

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