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Energetic ions in the close environment of Mars and particle shadowing by the planet

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THE twin-telescope particle-detector system, SLED, aboard Phobos 2 recorded flux enhancements in the range 30–350 keV in the same general location in the close environment of Mars, over eight days at ~900 km altitude in three successive elliptical orbits. Here we present possible interpretations of these observations. Energy-related particle shadowing by the body of Mars was also detected, and the data indicate that this effect occurred in <20% of the 114 circular orbits around Mars because of the nutation of the spacecraft. We discuss the influence of magnetic fields in allowing particles to reach the detector under potentially screened conditions.

The charged-particle detector SLED aboard the three-axis-stabilized Phobos 2 spacecraft was designed to measure the flux of ions and electrons simultaneously in the 30 keV to a few MeV range[1]. The instrument used silicon surface barrier detectors, two in each of the two telescopes viewing in the same direction. One telescope (Te 2) was covered by a thin Al-foil ($500 \mu g\ cm^{-2}$ Al on Mylar) whereas the other telescope (Te 1) was 'open'. The front detectors of both telescopes were covered by a $15 \mu g\ cm^{-2}$ Al-layer. Low-energy protons and electrons could be distinguished[2], as the foil-telescope stopped ions up to 350 keV (with respect to protons) due to the Al-foil and to the Al-layer on the front detector. The geometric factor of each telescope was $0.21\ cm^2$ ster and the FOV (field of view) axis, with a 40° apex angle, was in the ecliptic plane at 55° to the west of the sunward direction (nominal direction of the interplanetary magnetic field at Mars).

Back detectors were used to discriminate particles which penetrated the front detectors. In addition, each telescope was shielded by $5.6\ g\ cm^{-2}$ Al and Ta to prevent protons with energies <70 MeV and electrons <10 MeV from reaching the detector systems. Thus, six different energy channels for each telescope could be defined. In the open telescope Te 1, ions and electrons were recorded over the following ranges: channels C1 (30–50 keV), C2 (50–200 keV), C3 (200–600 keV), C4 (0.6–3.2 MeV), C5 (3.2–4.5 MeV), C6 (>30 MeV). In the foil-covered 'electron' telescope Te 2, the energy ranges covered by individual channels were very similar to the above. Channels 6 in both telescopes represent the count rates of the back detectors. In Te 2, protons with energies <350 keV, helium < 1.6 MeV and oxygen ions <8 MeV were stopped in the Al-layers. SLED was the first instrument to approach Mars as closely as 867 km, capable of measuring particles at energies ⩾30 keV (refs 3–5).

During the interval from switch-on (25 July 1988) until arrival at Mars (29 January 1989), SLED monitored interplanetary intensity variations with signatures typical of solar minimum conditions (co-rotating interaction regions) under gradual replacement by signatures characterizing solar maximum conditions (produced by transient events such as flares and coronal-mass ejections). Figure 1 provides an example of solar-flare-related particle enhancements recorded by SLED in C3 and C6 of Te 1 when close to Mars in successive circular orbits around the planet during March 1989. These data resemble those observed near the Earth by the satellite GOES 7 (ref. 6).

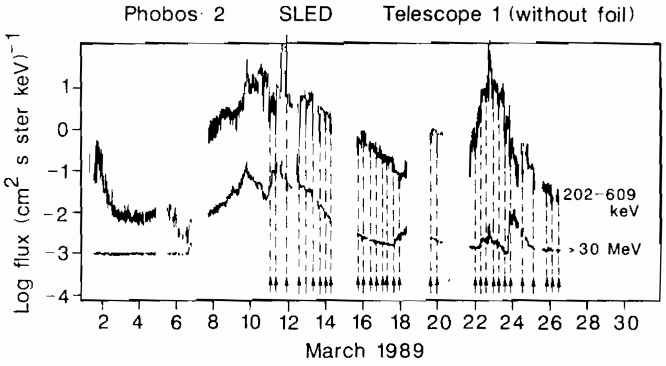

FIG. 1 In the circular orbits around Mars (~6,900 km) in March 1989 the particle fluxes observed by SLED were enhanced because of solar and interplanetary activity. Arrows (bottom) indicate significant depressions in flux resulting from the shadowing by the body of the planet.

In addition to observations during the cruise phase, particle measurements were also carried out during four elliptical orbits about Mars, 1–14 February 1989 (pericentre 867 km), and during the following single elliptical and 114 circular orbits (height above Mars 6,000 km). At the time of the first close elliptical orbit, the environment of the planet was greatly disturbed by the presence of particles of solar origin with energies up to a few MeV. Figure 2 (left-hand panels) shows data obtained during the relatively quiet interplanetary conditions characterizing orbit 2 and in more disturbed conditions for orbits 3 and 4. Complementary drawings showing the spacecraft trajectory in polar coordinates (times indicated are in UT) and the position during each orbit of the pericentre (PC), as well as the locations during orbits 2 and 3 of the bow shock and magnetopause, are presented in the right-hand panels. These latter data were provided by the cold plasma (TAUS) and magnetic field (MAGMA) experimenters. Figure 2 shows that, on 5 February 1989, a well-defined enhancement in fluxes increasing by a value of about two orders of magnitude and a duration of 8 min was recorded near pericentre in Te 1, C1 (30–50 keV), when the spacecraft was ~900 km above the planet. A less pronounced peak of about half an order of magnitude was recorded in C2 (50–200 keV). No enhancement was observed in the foil telescope Te 2, so that the increases recorded in Te 1 seem to have been produced by ions in the range 30–200 keV.

In orbit 3 (see Fig. 2) particle fluxes increased in Te 1, channels 1–3, again near pericentre. The duration of this effect was ~26 min. The largest enhancement occurred in the lowest energy range. The peaks of the enhancements in C2 and C3 occurred ~5 min earlier than that in C1. No special response was observed in Te 2.

In orbit 4 there was a telemetry gap close to pericentre but, as shown in Fig. 2, from after about 4 min, the declining phase of a flux enhancement was present in the data of Te 1, C1. Again, Te 2 showed no flux enhancement.

Positive responses in Te 1 and no responses in Te 2 at the times of pericentre passages may suggest pulse pile-up caused by lower-energy particles[7]. For SLED, baseline restoration is applied, the pulse-shaping time constant is 0.3 μs, the pulse length is 1 μs, and the coincidence resolution time is 1 μs. These factors prevent a pulse pile-up up to 10^5 c.p.s. The maximum fluxes observed near pericentre, however, do not exceed 10^3 c.p.s.

The fact that particle increases were recorded by Te 1 in the same general location, <900 km above the planet over ~8 days, therefore suggests the existence of a zone of enhanced radiation inside the martian environment. By identifying the nature and origin of this radiation, SLED could make an important contribution to the solution of an essential, yet unresolved, question concerning the geophysics of Mars, namely whether or not this planet has an intrinsic magnetic field and thus a magnetosphere, like the Earth.

If Mars indeed possesses a magnetosphere, these observed enhancements could represent a zone of trapped ion radiation (30–350 keV) similar to the van Allen belt in the inner part of

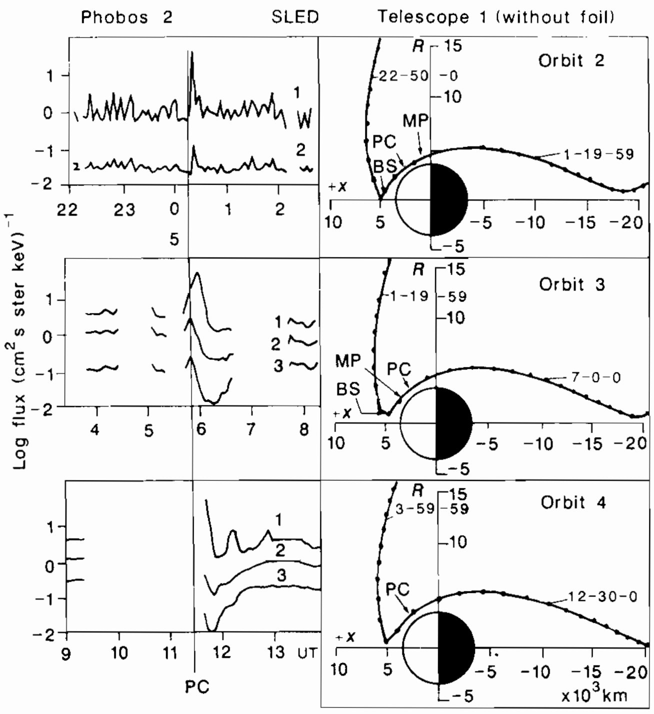

FIG. 2 Particle fluxes (left-hand panels) measured with Te 1 in the highly eccentric orbits 2, 3 and 4 at 4, 8 and 11 February 1989, respectively. In all three orbits clear flux enhancements were observed just after passing pericentre (PC) at ~900 km altitude. The energy bands are: 1, 30-50 keV; 2, 50-200 keV; and 3, 200-600 keV. The right-hand panels show for the same periods the radial distance *R* (in 1,000 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.

the Earth's magnetosphere. In the absence of unambiguous data concerning the overall structure of the ambient magnetic field, this possibility is not excluded. Because the gyroradii of these ions are approximately equal to the height of the spacecraft above Mars, however, these particles could only be quasitrapped, as they would be quickly lost because of their interaction with the dense atmospheric layers of the planet. This provides one possible explanation of the observation that, during orbit 3, the position of maximum flux recorded in the channels of Te 1 shifted with time towards lower energies, with the largest flux detected in the lowest-energy channel. On the other hand, the interaction of a martian magnetosphere with the interplanetary magnetized medium would possibly also lead to a local and sporadic merging of planetary with interplanetary magnetic field lines at the front side of the planet and thus, like at Earth, to an acceleration of charged particles. This mechanism could conceivably provide a source for the observed <350 keV ions, which could then propagate along the magnetopause boundary layer from the day to the nightside of the planet, as already observed in the case of the Earth's magnetosphere[8]. It is interesting to note that, at the part of the orbital trajectory concerned, SLED viewed directly along the surface of the magnetopause.

A more general explanation concerning the origin of these observed enhancements could alternatively rest in the fact that the magnetic-field observations indicated a pronounced compression of field lines close to the planet[9]. Such a compression would also increase the density of the ambient plasma and could simultaneously lead to an adiabatic acceleration of suprathermal particles to keV energies inside the martian environment. The acceleration of martian ions, such as oxygen, by the pick-up process in the solar wind can be neglected (provided no additional acceleration by other processes is imposed), as the expected energy would be ~60 keV and therefore below the threshold of the detectors with respect to oxygen.

At present other, more mundane, explanations cannot be ruled out entirely: for example, the observed enhancements could simply be caused by local changes in the angular distribution of particles as the spacecraft traversed different plasma regimes. For directed flux, an intensity enhancement would be observed if the angle between the flow direction and the instrument aperture became favourable. As is well known, the magnetic field changes its direction at the magnetopause quite substantially. Moreover, the possibility that sunlight reflected from the body of the planet (rather than from its thin atmosphere) may have contributed to the observed intensity increases cannot be excluded entirely. As the front detector of Te 1 is only shielded by 15 μg cm^{-2} Al, this detector will be sensitive to sunlight. However, the observed maximum fluxes near pericentre during orbit 3 cannot solely be caused by photons. Because photons will normally not produce a time dispersion in the time-intensity profiles, and the photon fluxes reflected from Mars, when taking the photon fluxes of the Sun at 1 AU (ref. 10), the albedo of Mars of ~10% and the characteristics of SLED into account, can hardly contribute to the observed count rates of $\sim 10^3$ c.p.s. and, at the same time, provide responses to C3 (200-600 keV). Yet the effect of sunlight must be investigated in more detail when adequate information concerning the attitude of the spacecraft becomes available. Finally, the possibility that the observed intensity increases are a result of bremsstrahlung[5], produced by low-energy electrons trapped along magnetic field lines, can be excluded, as the electron telescope Te 2 did not detect any electron fluxes.

An additional feature shown by the data of Fig. 2 from orbits 3 and 4, is the depression in fluxes by about one order of magnitude, which is seen particularly clearly in the data of Te 1, C3, C4 and C5. Although, as mentioned above, particle enhancements were not detected in Te 2, the depressions in fluxes recorded by Te 1 were clearly present in the data of C3 and C4 of Te 2. Again, depressions in fluxes recorded during orbit 4 in Te 1, C2, C3, C4 and C5 had well-defined counterparts in Te 2, C3 and C4. These decreases were energy-dependent in both telescopes.

Shadowing[11] by the planet Mars over that part of the orbit where the apertures are directed towards the planet is involved in producing these observed depressions in intensity. It is noted that data taken during 114 circular orbits at an altitude above the planet of 6,000 km indicate that marked decreases in the particle fluxes occurred in <20% of these revolutions, probably because of the nutation of the spacecraft. Successive instances of the occurrence of particle shadowing during the succession of flare-related particle enhancements recorded by SLED when in circular orbit during March 1989 are indicated by arrows in Fig. 1. This sequence seems to indicate the influence of magnetic effects in allowing particles to arrive at the detector during disturbed interplanetary conditions, even in situations where the solid angle of the aperture of the instrument was completely filled by the body of the planet. □

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