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INTERPLANETARY VARIABILITY RECORDED BY THE SLED INSTRUMENT ABOARD THE *PHOBOS* SPACECRAFT DURING THAT PERIOD OF SOLAR CYCLE 22 CHARACTERIZED BY A TRANSITION FROM SOLAR MINIMUM- TO SOLAR MAXIMUM-DOMINATED CONDITIONS

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Abstract—Twin telescope particle detector systems SLED-1 and SLED-2, with the capability of monitoring electron and ion fluxes within an energy range spanning approximately 30 keV to a few megaelectron volts, were individually launched on the two spacecraft (*Phobos*-2 and *Phobos*-1, respectively) of the Soviet *Phobos* Mission to Mars and its moons in July 1988. A short description of the SLED instrument and a preliminary account of representative solar-related particle enhancements recorded by SLED-1 and SLED-2 during the Cruise Phase, and by SLED-1 in the near Martian environment (within the interval 25 July 1988–26 March 1989) are presented. These observations were made while the interplanetary medium was in the course of changing over from solar minimum- to solar maximum-dominated conditions and examples are presented of events associated with each of these phenomenological states.

1. INTRODUCTION

In July 1988, two similar three-axis stabilized spacecraft, one a back-up to the other, were launched to Mars and its moons by the Soviet Union. The mission, which was named *Phobos*, was the subject of large-scale international participation and its goals included: (a) remote sensing of the Martian surface and atmosphere in the visible, u.v., i.r. and gamma-ray bands; (b) rendezvous with the moon Phobos to obtain data on its surface and interior using a variety of techniques; (c) imaging of the Sun in X-ray, u.v. and visible wavelengths; and (d) monitoring of the interplanetary medium—including the composition of the solar wind, the spectra and anisotropy of solar cosmic rays, solar and cosmic gamma-ray bursts and interplanetary shock waves.

The object of the present paper is to provide a short description of the low energy ($\sim$30 keV–3.2 MeV) particle detector SLED, identical versions of which were flown aboard both spacecraft (SLED-1 aboard *Phobos* 2 and SLED-2 aboard *Phobos* 1), and to present a preliminary account of representative, solar-related particle enhancements recorded by these instruments during the cruise phase of the mission and in the near Martian environment from 25 July 1988 to 26 March 1989 (that is within the rising phase of solar cycle 22, which commenced in September 1986).

It is now understood from *in situ* studies carried out over the last decade in the interplanetary medium, that interplanetary variability at solar minimum is associated with co-rotating structures and coronal holes whereas, at solar maximum, the dominant influence is provided by the consequences of energetic solar flares (Roederer *et al.*, 1987). These conditions thus reflect quite different phenomenological circumstances. The transition interval between these states was anticipated by the international committee on Solar Interplanetary Variability (SIV) to take place in the calendar years 1988–1989. Thus, a 2-year program of world wide interdisciplinary studies, to include both spacecraft and ground-based observations, was planned for this period, with the aim of elucidating how the solar interplanetary state evolves from solar minimum- to solar maximum-dominated conditions. Since the SLED-1 and SLED-2 cruise phase and near Mars observations were made directly within the critical interval, detailed analyses of the complex data obtained by these instruments are pertinent to the SIV study program.

2. THE SLED INSTRUMENT

Each SLED sensor was based on the well-known principle of measuring the incoming flux (ions and electrons) in two telescopes comprising silicon surface barrier detectors. One telescope (Te 2) was protected by a foil, the purpose of which was to prevent low energy ions (<350 keV for protons; 1.6 MeV for He; 8 MeV for oxygen) from reaching the detectors while permitting the passage of electrons.

The second "open" telescope (Te 1) meanwhile recorded both ions and electrons above an energy threshold determined by detector noise. The absorber in front of the Te 2 detector was composed of 500 μg cm^{-2} Al on Mylar. The front detectors of both telescopes were covered by a 15 μg cm^{-2} Al layer. Count rate differences between the telescopes, which were mounted to observe in the same direction, enable protons and electrons to be distinguished according to a method developed by Anderson *et al.* (1978). In this connection it is noted that the detectors were at a temperature of $<10^{\circ}$C throughout the mission while a special heater was provided to switch on automatically if the platform temperature fell below the operating limit for the detectors.

Each telescope incorporated a front (A) and back (B) detector mounted coaxially. The front detector in each telescope used four discriminators, thus providing four separate energy thresholds, A1–A4. Single back detectors (B1) 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 then be defined; see Table 1. Channel 6, in each telescope, represented the count rate of the back detector.

Figure 1 shows the telescope design. The A and B detectors were mounted coaxially in the cylindrical compartment where they were protected by a 5.6 g cm^{-2} aluminium and tantalum shield (except for a hole underneath the aperture). This shield acted to prevent protons with energies <70 MeV and electrons <10 MeV from reaching the detector systems. The aperture had an internal structure to reduce scattering of light and electrons. Light protection was provided by a thin sheet metal helmet mounted on top of the baffle. The geometric factor of each telescope was 0.2 cm^2 sr and the field-of-view axis, with a 40° apex angle, was tilted in the ecliptic plane with respect to the spacecraft–Sun line at 55° to the West of the Sun (the nominal direction of the interplanetary magnetic field at Mars). A detailed description of the instrument is contained in McKenna-Lawlor *et al.* (1990).

3. THE CRUISE PHASE

Phobos 1 and *Phobos* 2 were launched on 7 July and 12 July 1988, respectively, from the Baikonur Cosmodrome using Proton rockets. Following injection of the twin spacecraft into the Earth–Mars transfer trajectory, the SLED instruments were, after a period of approximately 12 days (to allow for outgassing), activated by command on 19 July at 00:30 U.T. (SLED-2) and on 23 July at 05:59 U.T. (SLED-1). Each instrument performed nominally throughout the operating lifetime of its associated "mother" spacecraft.

Table 1.

Telescope without foil (Te 1)	Telescope with foil (Te 2)
34–51 keV ions and electrons	38–51 keV electrons + 350–400 keV protons
51–202 keV ions and electrons	51–204 keV electrons + 400–500 keV protons
202–609 keV ions and 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)

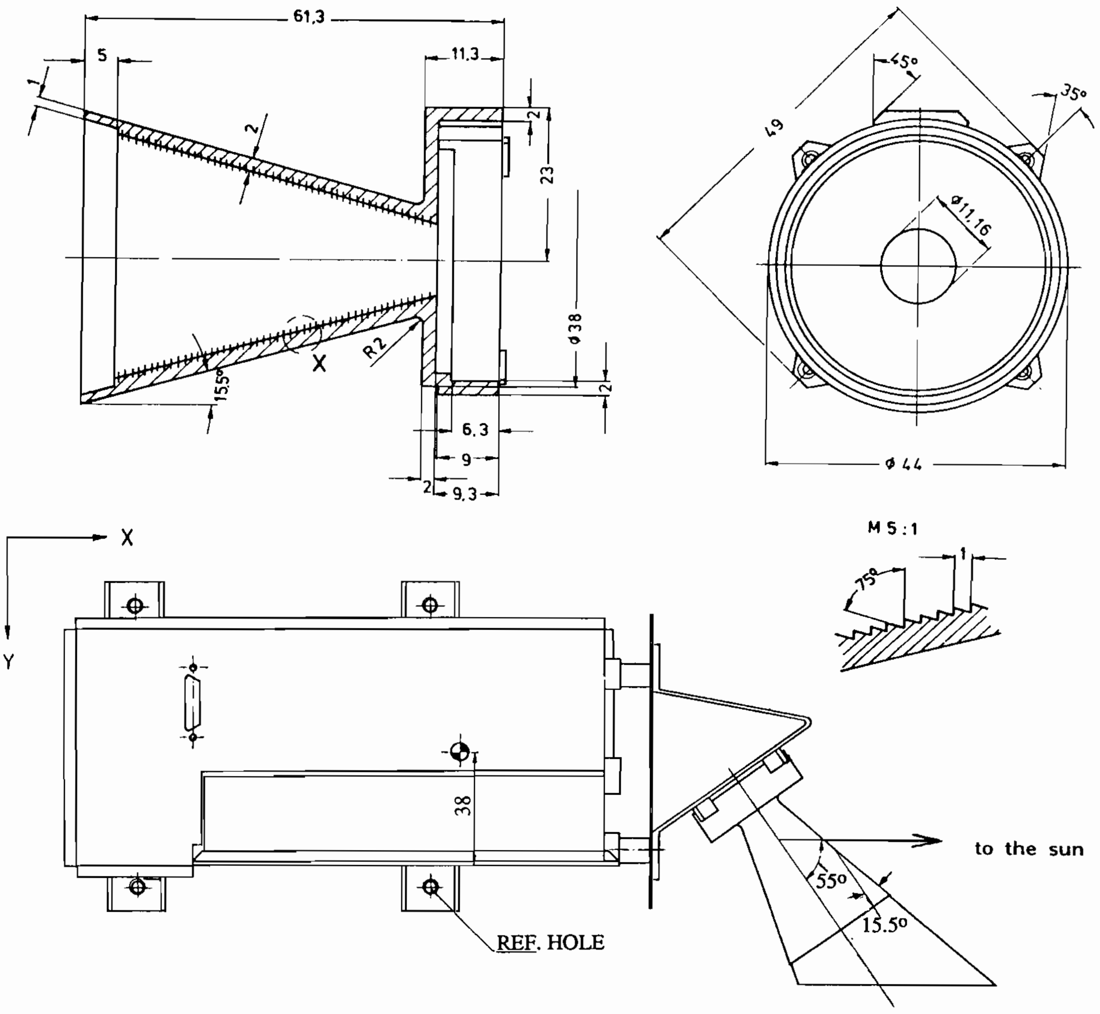

FIG. 1. (TOP) ; SCHEMATIC DRAWING OF A SLED TELESCOPE ; (BOTTOM) SCHEMATIC DRAWING OF THE SLED INSTRUMENT (LEFT) ; DETAIL OF THE INTERNAL TELESCOPE STRUCTURE (RIGHT).

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 29 January 1989 into a series of four highly eccentric orbits around Mars with a pericenter of approximately 867 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 (114 rotations). After two intermediate corrections of the circular orbit on 7 and 15 March, respectively, the spacecraft was transferred on 21 March to a quasi-synchronous orbit (i.e. an orbit around Mars practically in synchronism with Phobos). Ground connection with the spacecraft was lost at the end of March.

4. THE OBSERVATIONS

During the total *Phobos* Cruise Phase (7 July 1988–29 January 1989), SLED-1 from 19 July 1988 to 29 January 1989 and SLED-2 from 23 July 1988 to 28 August 1988, monitored intensity variations in particle counts in the interplanetary medium (maximum time resolution 230 s) in the various energy channels listed in Table 1. In the Martian environment, SLED-1 monitored particle fluxes in the elliptical and circular orbits about the planet over the interval 29 January to 26 March 1989.

Figure 2 shows representative data (integration time 230 s) recorded by SLED-1 during the cruise phase over the period from 25 July until 25 October

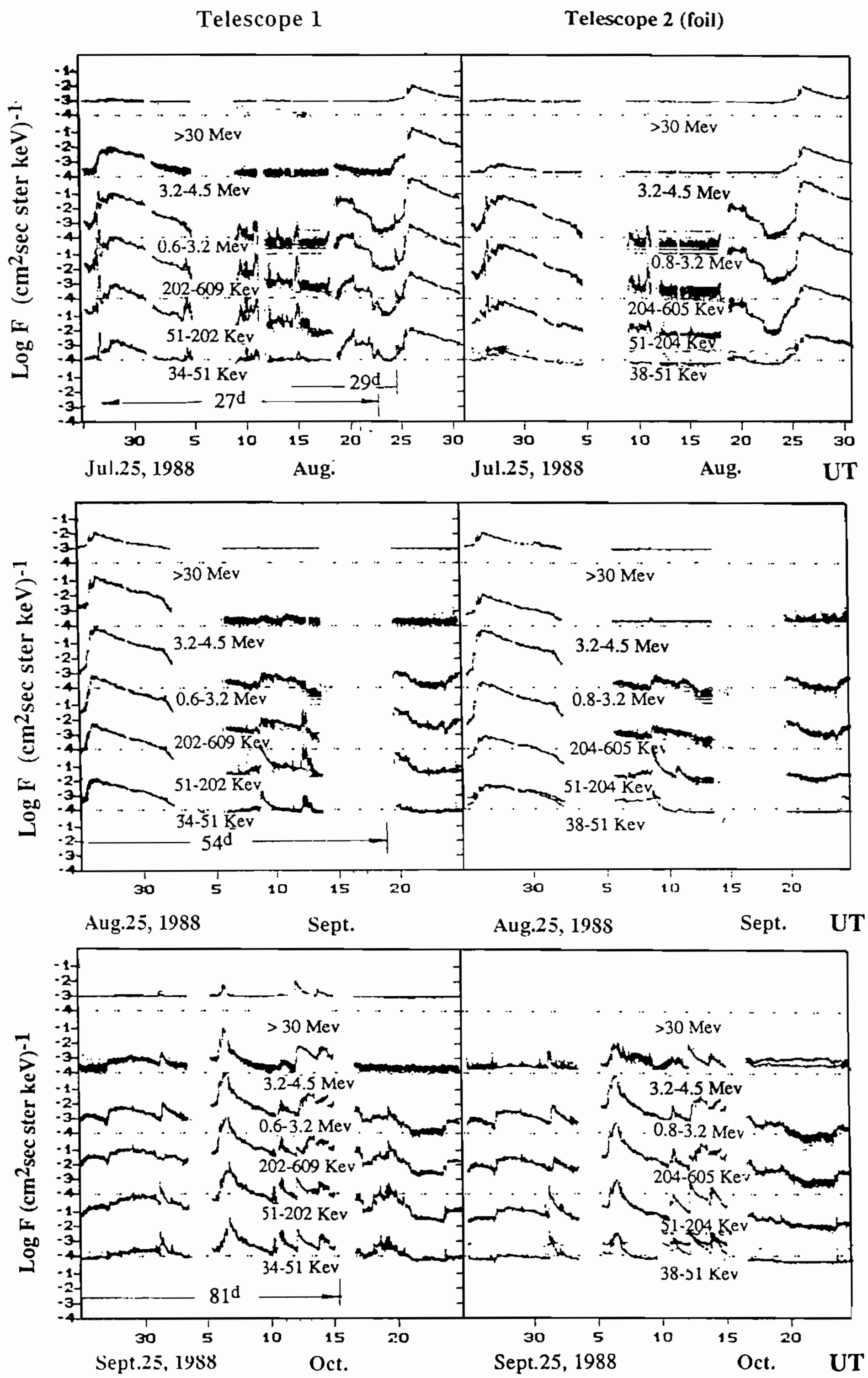

Fig. 2. Particle data recorded by SLED-1 in each of the six channels of Te 1 and Te 2 during the period 25 July–25 October 1988.

1988. The time-scale selected is chosen to optimize the detection of possible solar rotation-related periodicities in the data. Gaps in the record correspond to intervals when the instrument was switched off during special spacecraft operations. The data presented indicate that the interplanetary medium was greatly disturbed during 1988 and the first challenge posed by the records is to try to distinguish between signatures produced by co-rotating events and by transient streams.

Starting at the beginning of the observation period illustrated, it is noted that a well-defined spike appeared clearly in the low energy channels of Te 1 and Te 2 on 26 July at the commencement of a slowly rising enhancement. Figure 3 shows this spike on a somewhat enlarged time-scale as it was recorded by SLED-1 and SLED-2, respectively, in Te 1. These records appear to be very similar and differences between them can be attributed to the 5 day interval separating the two spacecraft carrying the individual instruments. The event began simultaneously in each of four channels and displayed the steep-sided profile characteristic of a co-rotating interaction region. The succeeding well-defined particle peak visible in Fig. 2 exhibits an exponential decay typical of a flare event.

Figure 4 (top) shows differential energy spectra recorded by SLED-1 in Te 1 and in Te 2 during the spike. Corresponding data relevant to the associated enhancement are shown beneath. 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 still have to be made and the influence of electron fluxes on the shape of the spectra assessed. Nevertheless, the data of Te 1 provide some support for the idea that the two populations of particles were different and it is suggested (a) that the energetic particles in the spike were accelerated in the forward and reverse shocks associated with a co-rotating structure and (b) in the absence of time dispersion in the stimulation of individual channels in the associated enhancement, that the particles concerned were trapped behind the co-rotating structure and recorded by the SLED instruments as the double event swept past each spacecraft.

As shown in Fig. 2, approximately 29 days after the double event, a second complex signature comprising a spike and an associated enhancement, also characterized by a "flare like" exponential decay, was recorded by SLED-1. Figure 5 shows the preliminary (see above), differential energy spectra measured by Te 1 and Te 2 during the spike (top) and during the following enhancement (bottom). The spectra presented in Fig. 5 (top) are similar to those recorded by SLED 29 days earlier although with somewhat reduced flux levels, and it seems possible that we are seeing a return of the same co-rotating region. The characteristics of the associated enhancement are, however, significantly different from those recorded during the July event. Differences include different rise-times, different velocity dispersion and the presence of >30 MeV particles in the August event. It is suggested that a likely source of the particles concerned in this case was in long-lived, background, flare activity taking place in a region at the East limb of the Sun which, as reported by the Space Environment

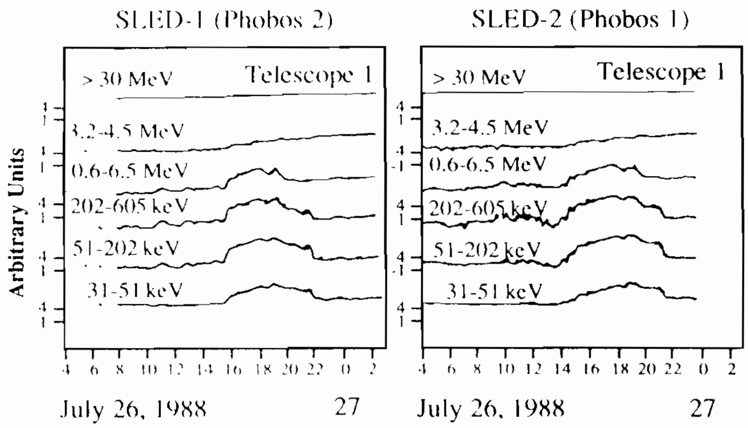

FIG. 3. PARTICLE DATA RECORDED BY SLED-1 (*Phobos* 2) DURING 230 s INTEGRATIONS IN EACH OF THE SIX CHANNELS OF TE 1 AND CORRESPONDINGLY BY SLED-2 (*Phobos* 1) IN EACH OF THE SIX CHANNELS OF TE 1, DURING THE PERIOD 04:00 U.T. 26 JULY–04:00 U.T. 27 JULY 1988.

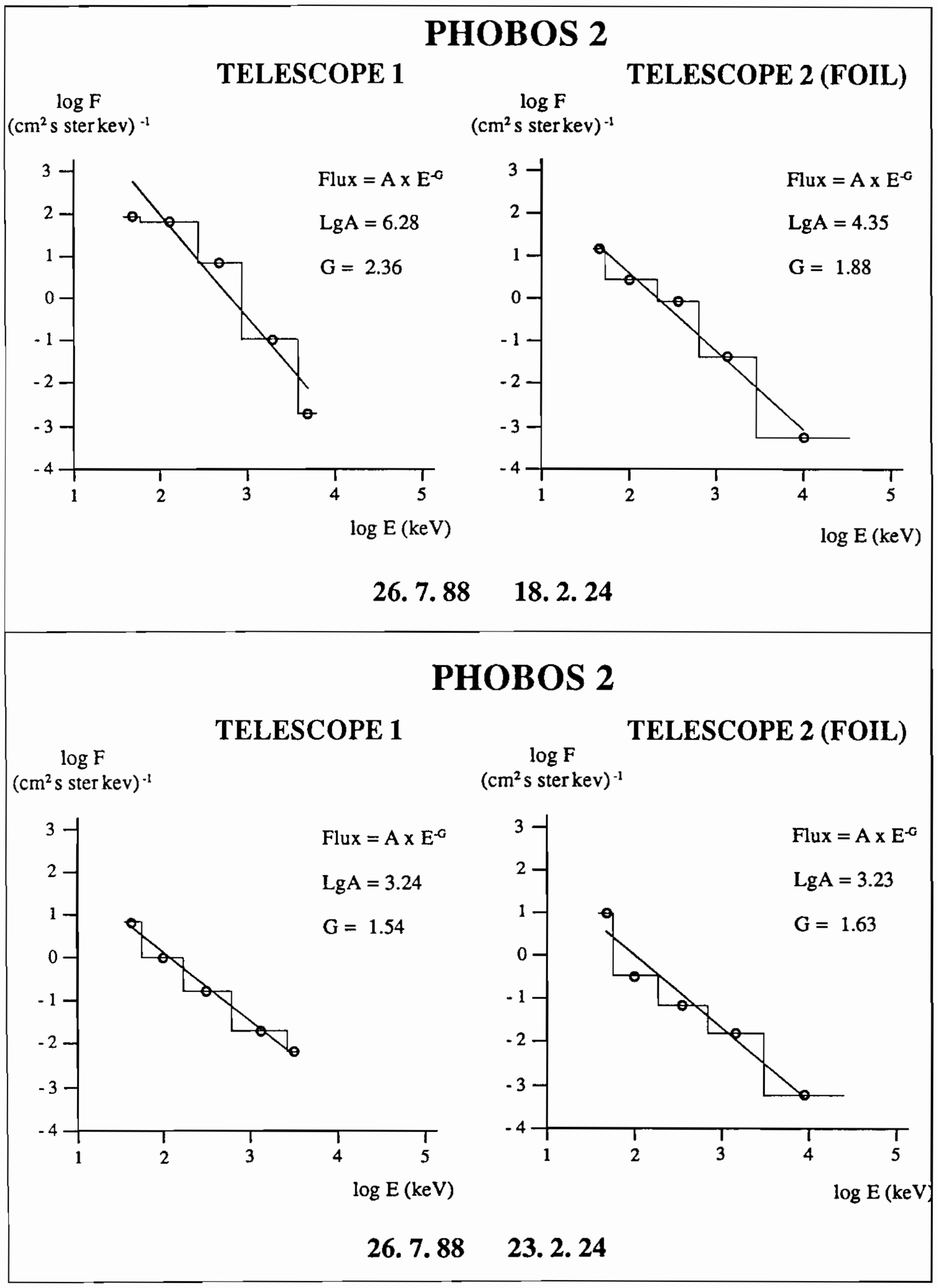

Fig. 4. Differential energy spectra for data acquired by SLED-1 during 230 s integrations on 26 July 1988 at 18:02:24 U.T. (top) and at 23:02:24 U.T. (bottom) in Te 1 and Te 2.

Services Center at Boulder, was associated with the production, over many (relevant) days, of energetic particles.

A further example of a double event comprising a spike and associated enhancement was recorded by SLED-1 on 29 January when the spacecraft was injected into its first elliptical orbit about Mars. Figure 6 presents the record obtained by SLED-1 in channel 4 spanning the energy range 0.6–3.2 MeV. These data are compared with data obtained concomitantly by

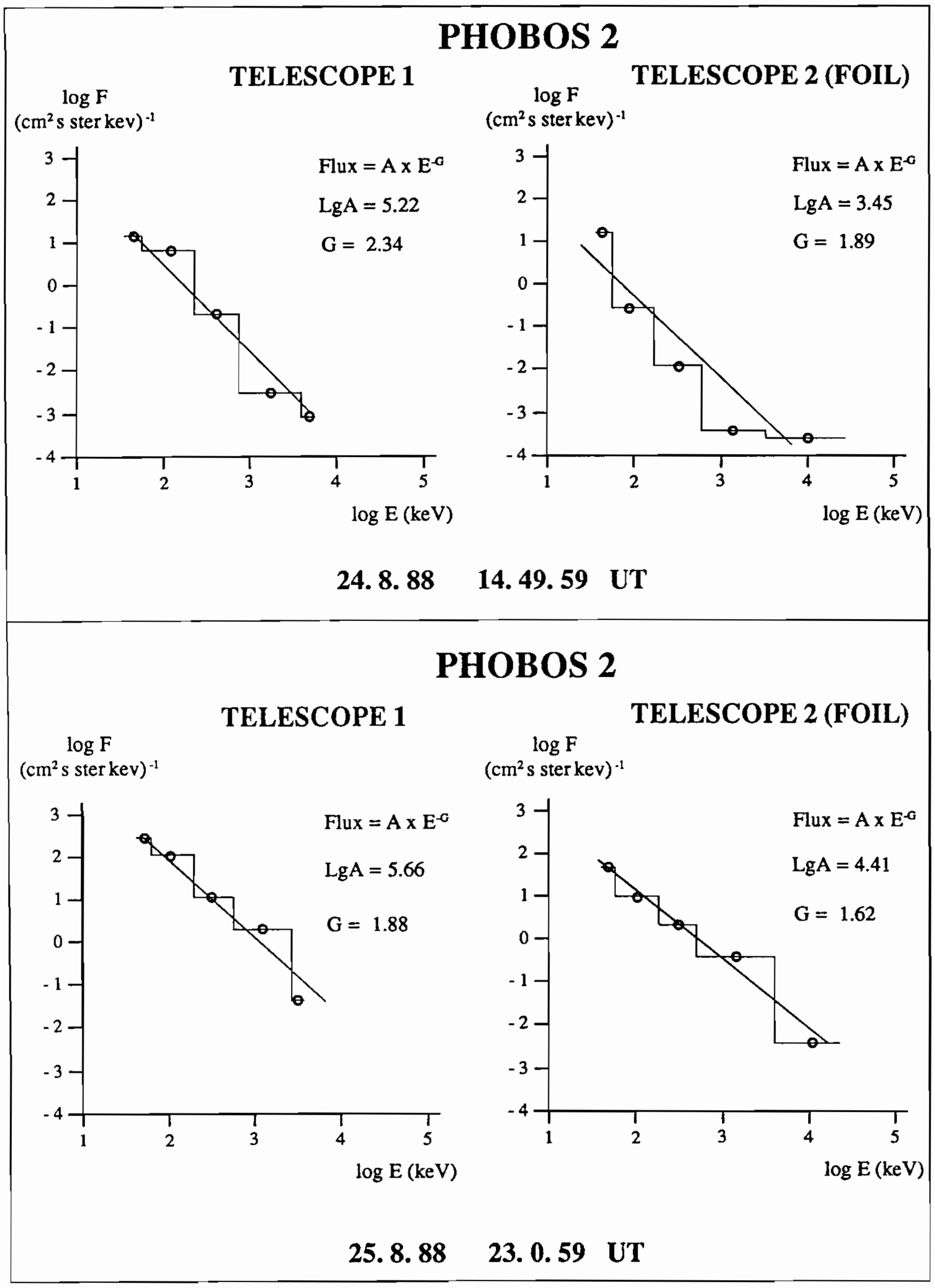

FIG. 5. DIFFERENTIAL ENERGY SPECTRA FOR DATA ACQUIRED BY SLED-1 DURING 230 s INTEGRATIONS ON 24 AUGUST 1988 AT 14.49.59 U.T. (TOP) AND ON 25 AUGUST 1988 AT 23.0.59 U.T. (BOTTOM) IN TE 1 AND TE 2.

LET-2 (the Low Energy Telescope experiment on *Phobos* 2, see Marsden *et al.*, 1991) in its energy channel 0.9–1.2 MeV. The LET data presented in Fig. 6 were recorded (236 s integration time) while viewing in practically the same direction (60° W of the Sun line) as did SLED (55° to the West). The scan plane of the LET platform was, however, tilted with respect to the ecliptic by 12° to secure an unobstructed field of

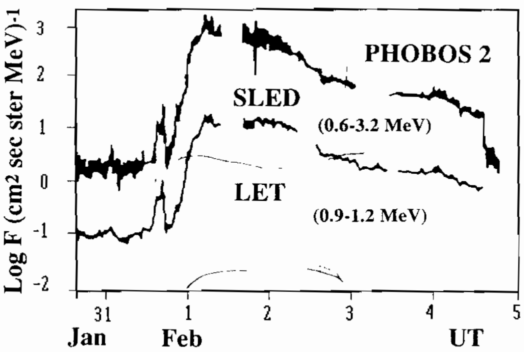

Fig. 6. Particle data recorded by SLED-1 in Te 1, channel 4 (0.6–3.2 MeV) and by LET-2 (0.9–1.2 MeV) from 31 January to 5 February 1989.
The SLED data are shown offset by a factor of 10 from the LET data for clarity of presentation. In the channels shown, the fluxes recorded differed from each other by less than a factor of two.

view. The close correspondences between the SLED-1 and LET-2 data show the complementary functioning of both instruments in this part of the energy spectrum. Our preliminary interpretation of the particular events illustrated is similar to that suggested above in association with the records of July and August 1988.

Particle enhancements associated with major flaring were identified in the SLED records during October and December 1988 and in January and March 1989. Figure 7 shows flare-related signatures recorded over the interval 6–26 March in channel 3 (202–609 keV) and in channel 6 (>30 MeV) of SLED-1 while the spacecraft was in circular orbit about Mars. The enhancements were associated with activity in solar region 5395 which rotated onto the disk on 6 March and thereafter quickly produced an X 15 class 3B flare at 13:54 U.T., followed by a sequence of energetic flares. The recurrent particle decreases, marked by arrows and dotted lines, are due to particle shadowing by the body of Mars as the spacecraft performed successive circular orbits about the planet (see also Afonin *et al.*, 1989).

Comparisons show that the SLED and LET data obtained during the March events were closely complementary in the lower energy channels of LET. An analysis by Marsden *et al.* (1990) of the enhancements recorded by the LET instrument in that channel which is close to SLED's channel 3, namely their proton channel 0.9–1.2 MeV (and also in other LET records), suggests that specific increases in particle fluxes at 18:00 U.T. on 6 March, 00:30 U.T. on 9 March, 21:25 U.T. on 10 March, 05:00 U.T. on 11 March, 19:00 U.T. on 17 March and 20:45 U.T. on 23 March, were associated with particular flares. An enhancement at 20:15 U.T. on 9 March was identified as an energetic storm particle event that coincided with the passage of an interplanetary shock at *Phobos* 2. The SLED-1 observations presented in Fig. 7 are quite consistent with these interpretations.

A combined in-depth study of LET and SLED data should provide interesting insights into particle propagation during March 1989, which included, on 6 March, the most energetic solar cosmic ray event yet recorded during solar cycle 22 (and the second most energetic such event recorded at the Earth since

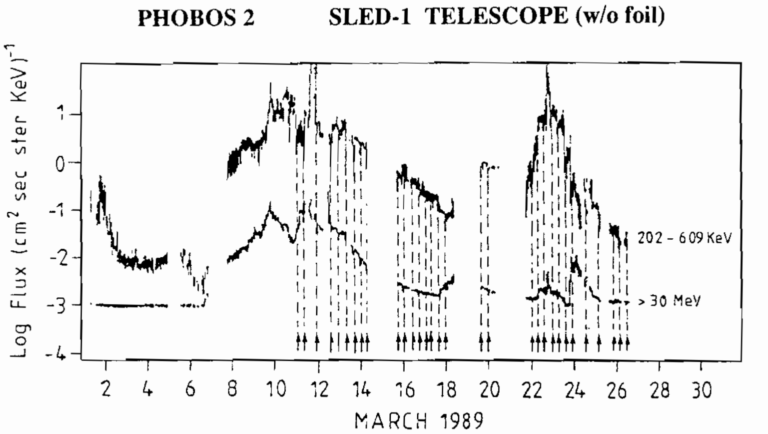

Fig. 7. Particle data recorded by SLED-1 in Te 1 channel 3 (202–609 keV) and in channel 6 (>30 MeV) from 1 to 26 March 1989.
Dotted vertical lines, terminating in arrows, indicate recurrent depressions in flux resulting from cyclic shadowing by the body of the planet as the spacecraft executes circular orbits around Mars.

ground-based observations began). Although, as the preceding representative data have indicated, it is possible to distinguish in certain cases with reasonable certainty between the signatures produced by co-rotating events and by particle-associated flares, the complexities and possibility of mis-identification posed by the necessity to analyze a large (>8 month) sample suggests that the task may best be accomplished by correlating the SLED observations not only with LET data, but also with those data simultaneously recorded by spacecraft at a variety of solar coordinates (e.g. ICE, IMP, SAKIGAKE and PVO). This technique was successfully used by Dreyer (1987) in a study of travelling interplanetary phenomena (STIP) recorded during and before the solar maximum year. Optical solar data obtained aboard *Phobos* and on the *Solar Maximum Mission*, as well as energetic particle measurements made at the Earth, should further elucidate the correlation between spatial and temporal changes on the Sun and those *in situ* variations in the interplanetary medium identified in the SLED records.

5. CONCLUSIONS

The SLED-1 instrument closely monitored interplanetary variability in the energy range ~30 keV to a few megaelectron volts during the period from 23 July 1988 to March 26 1989. SLED-2 provided complementary observations from 19 July until 28 August 1988.

The observation intervals coincided with a period when the solar interplanetary medium was in the course of evolving from one solar cycle-dominated characteristic state to another (during the rising phase of solar cycle 22). Elucidation of the transition between the steady recurrent solar wind flow patterns characteristic of solar minimum and the transient flows, often related to energetic flare events on the Sun, encountered at solar maximum, are relevant to the international Solar Interplanetary Variability Study (SIV) mounted to study the transition of the interplanetary medium from solar minimum- to solar maximum-dominated conditions, 1988–1989.

As stated by the organizers of the SIV program, Roederer *et al.* (1987), "recent advances have led to a reasonable characterization of solar interplanetary conditions at solar minimum and at solar maximum and have established their grossly differing character". Therefore, the SIV Committee proposed specifically to focus attention on the transition between these two different states during the period 1988–1989.

The data discussed here which, through combining the observations of SLED-1 and SLED-2, extend, overall, from 19 July 1988 to 26 March 1989, have been shown to reveal, within this critical transition period, the onset of increasing solar activity against a relatively quiet interplanetary background, within which co-rotating streams can be clearly identified. In-depth investigation of these important SLED records, supplemented by simultaneous observations recorded aboard various other spacecraft and at the Earth, will permit us to monitor, despite the disturbances provided by an increasing incidence of transient events, those structures that co-rotate, sweeping past first one spacecraft, then another—thereby allowing us ultimately to seek to identify their source regions on the Sun. Co-ordinating the SLED observations with concomitantly recorded data may also enable us to identify changes in the inclination of the heliospheric sheet over the more than 8 month period covered by the observations and, thereby, provide us with insight as to how changing solar circumstances are intimately related to structures and events associated with the evolution of large-scale interplanetary variability.

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REFERENCES

Afonin, V., McKenna-Lawlor, S., Gringauz, K., Kecskemety, F., Keppler, E., Kirsch, E., Richter, A., O'Sullivan, D., Somogyi, A., Thompson, A., Varga A. and Witte, M. (1989) Energetic ions in the close environment of Mars and particle shadowing by the planet. *Nature* **341**, 616.

Anderson, K. A., Lin, R. P., Potter, D. W. and Heetderks, H. D. (1978) An experiment to measure interplanetary and solar electrons. *IEEE Trans.* **GE-16**, 153.

Dreyer, M. (1987) Study of travelling interplanetary phenomena (STIP) report. *Solar Phys.* **114**, 407.

Marsden, R. G., Afonin, V. V., Balazs, A., Erdös, G., Henrion, J. P. J., Richter, A. J. Rusznyak, P., Somogyi, A., Szali, S., Varga, A., Varhalmi, L., Wenzel, K.-P. and Witte, M. (1990) *Phobos* 2 energetic particle observations of the March 1989 flare events. *Proc.* XXI*st International Cosmic Ray Conference at Adelaide, Australia*, Vol. 5, p. 121. University of Adelaide.

Marsden, R. G., Wenzel, K.-P., Afonin, V. V., Gringauz, K., Witte, M., Richter, A. K., Erdös, G., Somogyi, A. J., Varga, A. and Varhalmi, L. (1991) Energetic particle composition measurements from *Phobos* 2: results of the LET experiment. *Planet. Space Sci.* **39**, 57.

McKenna-Lawlor, S. M. P., Afonin, V. V., Gringauz, K. I., Keppler, E., Kirsch, E., Richter, A. K., Witte, M., O'Sullivan, D., Thompson, A., Kecskemety, K., Somogyi,

A. J., Szabo, L. and Varga, A. (1990) The low energy particle detector SLED (– 30 keV–3.2 MeV) and its performance on the *Phobos* Mission to Mars and its moons. *Nucl. Instrum. Meth. Phys. Res.* **A290**, 217.
Roederer, J. G., Axford, W. I., Liu, C. H. and Smith, E. J. (1987) A Scientific Program to study large scale solar interplanetary variability during the transition from solar minimum to maximum (1988–1989). A Report of the SCOSTEP Committee on Solar-Interplanetary Variability.