Planet. Space Sci., Vol. 39, No. 1/2, pp. 57–66, 1991
Printed in Great Britain.

0032–0633/91 \$3.00+0.00
Pergamon Press plc

ENERGETIC PARTICLE COMPOSITION MEASUREMENTS FROM *PHOBOS* 2: RESULTS OF THE LET EXPERIMENT

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(*Received* 24 *April* 1990)

Abstract—The Low Energy Telescope (LET) experiment carried on board the *Phobos* spacecraft measured the flux, spectra and elemental composition of nuclei from hydrogen up to iron, in the energy range $\sim$1–75 MeV nucleon^{-1}. Isotope separation for helium was also achieved. We present the results of a study of solar energetic particle (SEP) composition using LET data acquired during the period July 1988 to March 1989. The set of particle events selected for study comprises six large solar flare events, two ^{3}He-rich events and two energetic storm particle increases associated with interplanetary shocks. Three of the six large flare events occurred during a period of unusually high solar activity in March 1989. In two of these events, large Fe/O ratios were measured (0.44 ± 0.05 and 0.95 ± 0.24). The Fe/O ratios determined for the complete set of large flare events show an inverse correlation with the spectral index of oxygen, suggesting that the acceleration mechanism that produces events showing enhanced heavy-ion abundances is different from that responsible for lower Fe/O ratios. Our results in the case of the ^{3}He-rich events are in agreement with earlier work, showing an enrichment in heavy ions relative to the average SEP composition. The abundances measured for the shock-associated increases are consistent with the acceleration of the ambient population of solar flare particles.

1. INTRODUCTION

The Low Energy Telescope (LET) experiment was originally included in the *Phobos* payload in order to provide in-ecliptic baseline data on solar energetic particles (SEP) and low energy cosmic ray nuclei for the *Ulysses* solar polar mission, scheduled at that time for launch in 1986. Carried aboard both *Phobos* spacecraft, the LET formed part of the ESTER experiment group (comprising the LET, SLED and HARP instruments) that returned complementary data covering a wide variety of charged particle populations and energies throughout the cruise phase and at Mars (Afonin *et al.*, 1990). Specific objectives of the LET investigation were (a) the measurement of intensity, energy spectra and composition of SEP in the range $\sim$1–75 MeV nucleon^{-1} and (b) the study of charged particle acceleration at travelling interplanetary shocks and corotating interaction regions. Secondary objectives included the study of cosmic ray gradients using simultaneous measurements from the two *Phobos* spacecraft, and the measurement of the anomalous component of galactic cosmic rays. Both LET instruments performed extremely well in flight and returned valuable data up to the time that contact was lost with the respective *Phobos* spacecraft. In the present paper, we concentrate on the results obtained by the LET experiment in the area of SEP composition, selecting three categories of events for study: (i) large flare events; (ii) ^{3}He-rich events; and (iii) interplanetary shock-related increases (energetic storm particle events) that were associated with two of the large flare events.

The elemental composition of solar energetic particles accelerated in large solar flares has been the subject of many investigations over the past two decades (e.g. Meyer, 1985; McGuire *et al.*, 1986, and references therein). One feature that has emerged from these studies is the large event-to-event variability in SEP composition, and in particular the Fe/O ratio. In general terms, this variability has been interpreted as being primarily due to rigidity-dependent effects which operate at the time of SEP acceleration and/or propagation, and which introduce mass (or charge) dependent biases that act upon a baseline composition characteristic of ordinary coronal material (Meyer, 1985). On the other hand, there is strong evidence that additional effects complicate this rather simple picture, particularly for He, which does not follow the same enrichment pattern as the heavier elements O through Ni.

In the case of SEP events showing enrichment in ^{3}He, previous studies have established a tendency for heavy ions to also be enriched relative to the SEP baseline composition for these events (reviews by Ramaty *et al.*, 1980; Kocharov and Kocharov, 1984; Mason *et al.*, 1986, and references therein). Mason *et al.* (1986) showed that the degree of heavy-ion enrichment is uncorrelated with the ^{3}He enrichment. These authors concluded that the heavy-ion enrichment is characteristic of the coronal composition at sites where ^{3}He-rich events originate, rather than being a consequence of an acceleration process that selectively heats ^{3}He. The results reported here both for the large flare events and the ^{3}He-rich events are in general agreement with those of previous studies. In particular, we confirm the event-to-event variability in the Fe/O ratio seen in large flare events. Furthermore, our results show an apparent inverse correlation between the magnitude of this ratio and the average differential energy spectral index. In the case of the two ^{3}He-rich events occurring during the observation period, we find a significant heavy-ion enrichment relative to the average SEP composition measured in large events. Finally, it has been proposed that the seed population for shock-accelerated ions possessing energies of several megaelectron volts nucleon^{-1} may not be suprathermal solar wind particles, as is the case at lower ($\sim$tens of kiloelectron volts) energies (Tan *et al.*, 1989), but rather the ambient solar flare particles. Our results are consistent with this hypothesis.

Details of the experiment and data analysis are given in Section 2, and the observations are described in Section 3 and discussed in Section 4.

2. INSTRUMENTATION AND ANALYSIS

The *Phobos* LET instrument comprises a four-element solid-state detector telescope operating in the double dE/dX vs E mode, surrounded by a cylindrical plastic scintillator anticoincidence shield. The telescope is shown in schematic form in Fig. 1. Detectors D1 and D2 are large area (6 cm^2) surface barrier devices having nominal thicknesses of 30 μm (D1) and 100 μm (D2), while D3 and D4 are 2-mm thick Li-drifted detectors of 10.0 and 12.5 cm^2 active area, respectively. The instrument has two basic energy ranges, the first (lower) corresponding to particles that stop in D2 (two-parameter mode) and the second (upper) corresponding to particles stopping in D3 (three-parameter mode). These are further subdivided to give counting rate information for protons (five channels), alpha particles (four channels), heavy ions (seven channels) and electrons (one channel); pulse height analysis (PHA) information is available for a subset of events. Owing to the restricted LET telemetry allocation, on-board particle identification of groups of species is employed to enhance the sample of rarer particles in the data stream (limited to two PHA events transmitted per minute). A summary of the LET data channels is presented in Table 1 and further details concerning the instrument can be found in Marsden *et al.* (1990b).

The SEP composition measurements reported in the present work are based in general on LET PHA data from the lower (single dE/dX vs E) energy range of the instrument. Individual element identification was performed for each PHA event using the standard technique of comparing the measured differential energy loss in one (or both) thin detector and the residual energy with reference data obtained from accelerator calibrations for selected species (in our case, He, O, Si and Fe). An interpolation procedure was then used to derive a fractional charge value. A typical LET charge spectrum obtained in this way is shown in Fig. 2. By summing all events having fractional charge values lying between upper and lower limits defined for each element, a PHA event count for that element corresponding to the time interval being analysed was computed. In addition, a correction was applied to the measured particle energy to account for energy losses in the two aperture foils. For species belonging to the same priority group, no count rate normalization is needed in order to derive meaningful abundance ratios from these PHA event counts. For elements belonging to different priority groups (He and O, for example), the count rate information corresponding to the respective groups was used to normalize the PHA sample.

In addition to the excellent charge resolution available, the isotopes ^{3}He and ^{4}He are well separated in the LET data. In order to obtain appropriate isotopic ratios, a fractional mass for each pulse-height analysed He event was computed using an iteration method developed by Cook (1980). After correcting

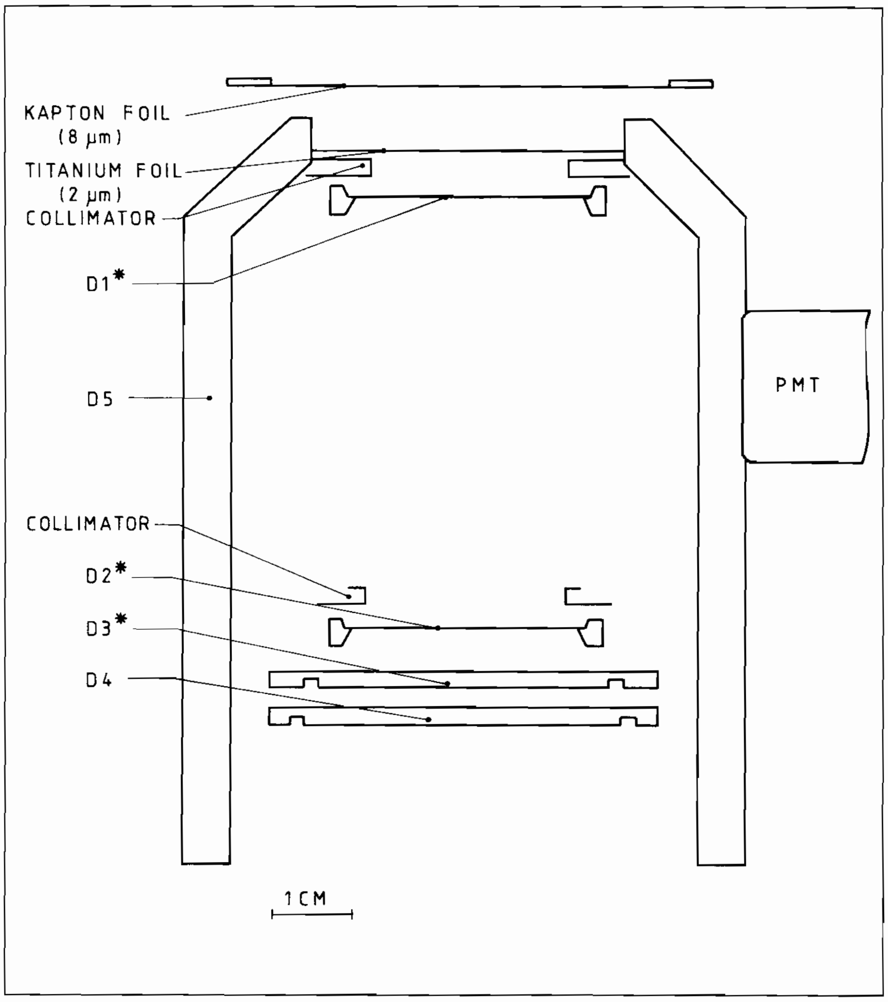

FIG. 1. A SCHEMATIC DRAWING OF THE *Phobos* LET TELESCOPE; *D*m* DENOTES A PULSE-HEIGHT ANALYSED DETECTOR.

for energy losses in the foils, separate PHA event counts for ^{3}He and ^{4}He were accumulated in two energy intervals, 2.2–3.8 and 4.0–10 MeV nucleon^{-1}. Figure 3 shows the mass spectrum in the lower of the two energy ranges for one of the ^{3}He-rich events discussed below.

3. OBSERVATIONS

The observations reported here were obtained during the 9-month interval from July 1988 to March 1989, the active lifetime of the *Phobos* 2 spacecraft. Throughout this interval, corresponding to the rising phase of Solar Cycle 22, solar activity was mainly moderate to high, and the particle increases recorded by the LET were largely due to solar flare events, although some CIR-related enhancements were detected.

3.1. *Large flare events*

For the present study, we have selected six large flare events, chosen so that the heavy ion fluxes yielded adequate statistics. ^{3}He-rich events were excluded, but no other selection criteria were applied. For two of the six selected events, a shock-accelerated population could be clearly identified in addition to the solar flare particles, and we have made a separate determination of the composition in these cases. Three of the six

TABLE 1. *Phobos* LET DATA CHANNEL SUMMARY

Channel No.	Code		Measurement		Time resoln (s)
1	P1	Proton	0.9–1.2	MeV	240
2	P2		1.2–3.0		240
3	P3		1.8–3.8		240
4	P4		3.8–8.0		240
5	P5		9.0–19		240
6	A1	Alpha	1.0–5.0	MeV nucleon^{-1}	240
7	A2		1.9–4.0		240
8	A3		4.0–9.0		240
9	A4		9.0–19		240
10	H1	Li, Be, B	2.3–5.2		1200
11	H2		5.2–26		1200
12	H3	C, N, O	3.2–7.5		1200
13	H4		7.5–39		1200
14	H5	$Z \geqslant 10$	3.9–9.5		1200
15	H6		9.5–50		1200
16	H7	$Z \geqslant 20$	12–75		1200
17	E1	e^-	0.35–1.5	MeV	1200
	PHA		Pulse height data		30

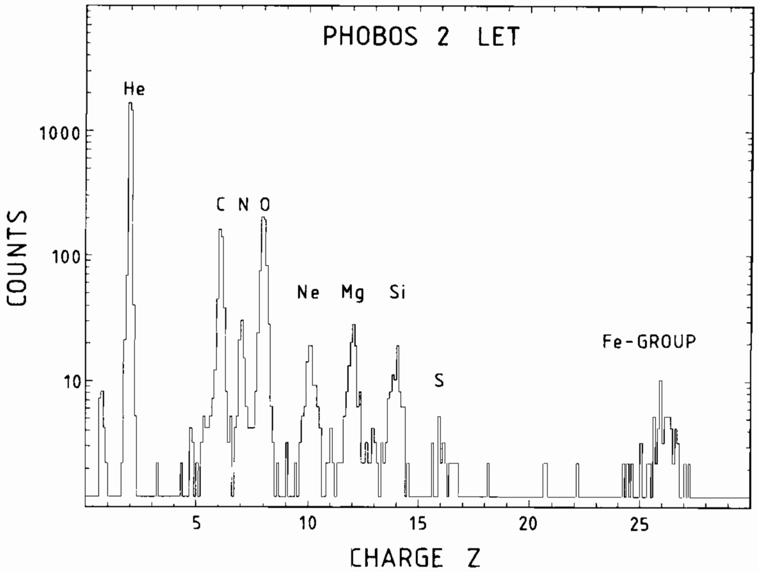

FIG. 2. CHARGE SPECTRUM CONSTRUCTED FROM LET PULSE HEIGHT DATA ACQUIRED ABOARD *Phobos* 2. Counts are offset by 1.2 for clarity. The spectrum as shown has not been normalized, whereby the amplitude of the peaks corresponding to the heavier elements (charge $\geqslant 10$) are enhanced relative to their true abundances. The energy range for ^{16}O nuclei is 3.4–7.9 MeV nucleon^{-1}.

flares occurred during a period of very high activity in March 1989 associated with Active Region 5395. A detailed description of *Phobos* LET observations of the March flare events is given by Marsden *et al.* (1990a). An overview of the periods analysed and event characteristics is given in Table 2. The corresponding time–intensity profiles for 1.8–3.8 MeV protons are presented in the three panels of Fig. 4. Also indicated in Fig. 4 are the averaging periods for the flare events (marked as F) and the shock-related

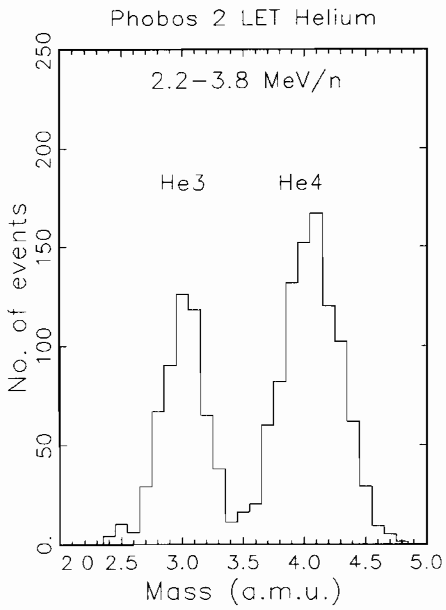

FIG. 3. MASS SPECTRUM FOR $Z = 2$ EVENTS IN THE ENERGY RANGE 2.2–3.8 MeV NUCLEON^{-1}, SHOWING THE EXCELLENT RESOLUTION OF ^{3}He AND ^{4}He.

TABLE 2. SUMMARY OF LARGE FLARE EVENTS

Event	Period Date/Time (U.T.)		Type	Flare	*Phobos* 2 posn r (a.u.)*	α (°)†
i	28 Aug. 1988– 01 Sep. 1988	22:45– 23:25	Flare	M2/E90	1.07	0
iia	17 Dec. 1988– 18 Dec. 1988	01:05– 03:25	Flare	1B/E37	1.45	30
iib	18 Dec. 1988 19 Dec. 1988	14:40– 14:10	Shock	—	1.45	30
iii	24 Dec. 1988 27 Dec. 1988	01:05– 01:05	?	—	1.47	35
iva	08 Mar. 1989– 09 Mar. 1989	01:05– 09:25	Flare	3B/E69	1.58	74
ivb	09 Mar. 1989– 11 Mar. 1989	11:25– 01:05	Shock	—	1.58	74
v	11 Mar. 1989– 14 Mar. 1989	05:45– 09:45	Flare	3B/E22	1.59	77
vi	24 Mar. 1989– 25 Mar. 1989	01:05– 00:25	Flare	3B/W28	1.60	82

* Heliocentric distance.
† Angle with respect to Sun–Earth line (East).

increases (marked as S). In principle, the averaging periods were chosen to include the whole flare event; however, data gaps and the presence of multiple increases precluded this in a number of cases.

3.2. ^{3}He-*rich events*

From a survey of 3-h averages of the ^{3}He/^{4}He ratio in the energy range 2.2–3.8 MeV nucleon^{-1}, determined from the He PHA data as described above, two

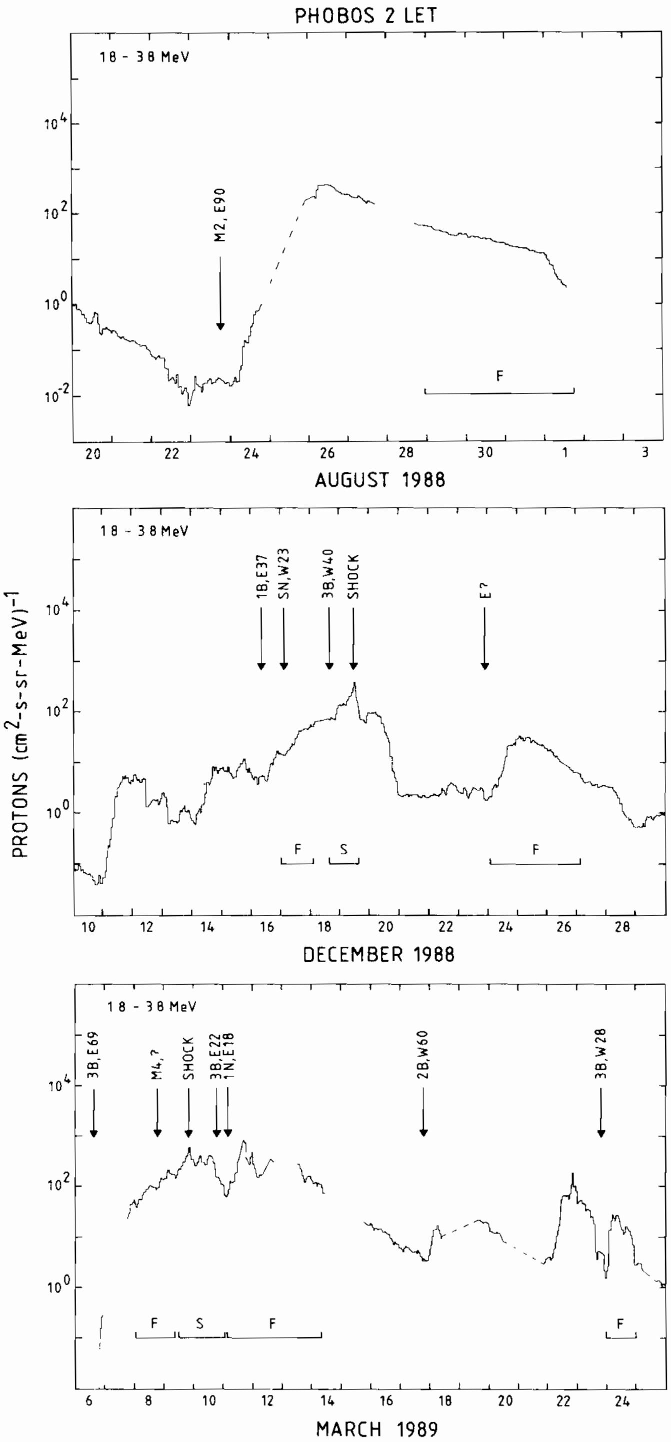

FIG. 4. PROTON INTENSITY IN THE ENERGY RANGE 1.8–3.8 MeV MEASURED BY THE LET ON *Phobos* 2 PLOTTED AS A FUNCTION OF TIME FOR THREE INTERVALS CONTAINING THE LARGE FLARE EVENTS INCLUDED IN THIS STUDY.

Time periods used for averaging are marked (F for flare events, S for shock events). Also shown are onset times for candidate progenitor flares (from *Solar Geophysical Data*).

TABLE 3. SUMMARY OF ^{3}He-RICH EVENTS

Event	Period Date/Time (U.T.)		$^3He/^4He$ (2.2–3.8 MeV nucleon^{-1})	Flare
i	08 Sep. 1988– 10 Sep. 1988	12:05– 12:05	0.55 ± 0.07	M1/W72
ii	01 Oct. 1988– 03 Oct. 1988	00:05 14:05	0.51 ± 0.05	M1/W75

periods of ^{3}He enrichment were identified, corresponding to small X-ray flare events. The characteristics of the two events, which were very similar in nature, are given in Table 3. Both events had associated type-II radio bursts, and originated close to the western limb.

3.3. *Shock events*

For two of the six selected large flare events, a shock-accelerated population could be clearly identified in addition to the ambient solar flare particles. The first of these shock events occurred on 19 December 1988, and is shown in the center panel of Fig. 4. An interplanetary shock passed the *Phobos* 2 spacecraft, located 30° E of the Sun–Earth line at a heliocentric distance of 1.45 a.u., at ~12:00 U.T. The X4/1B flare of 16 December (H_α max. 08:46 U.T.) that was most likely responsible for this shock also triggered a SSC event at the Earth on 17 December at 18:24 U.T. (*Solar Geophysical Data*). Assuming the same shock was involved in both events, we can derive shock velocities at the Earth and *Phobos* 2 of 1235 and 805 km s^{-1}, respectively. The difference in derived velocities could be due to a significant deceleration between 1 and 1.45 a.u., or asymmetry of the shock front. The proton intensity profile observed at *Phobos* shows the typical characteristics of an energetic storm particle (ESP) event. The second ESP event was observed at 20:15 U.T. on 9 March 1989 by the LET on *Phobos* 2, which was located approximately off the Sun's East limb as seen from the Earth, at a heliocentric distance of 1.6 a.u. This event coincided with the passage of an interplanetary shock at *Phobos* and, as in the previous case, an associated SSC event was observed at the Earth (8 March, 17:55 U.T.). Again, assuming the same flare (an X15/3B on 6 March/13:54 U.T.) was responsible for both the ESP and SSC events, we deduce shock velocities of 800 km s^{-1} (Earth) and 850 km s^{-1} (*Phobos*), implying a uniform radial expansion over at least 90° longitude.

4. RESULTS AND DISCUSSION

4.1. *Large flare events*

The SEP abundances of He, C, N, O, Ne, Mg, Si and Fe relative to oxygen for the six flare events and two shock-related increases are listed in Table 4. The results refer to the energy interval 4.25–8.5 MeV nucleon^{-1}. Also given in Table 4 is the differential energy spectral index for oxygen γ_O as determined from the best-fit power law for each event. With the exception of events v and vi, the abundances measured in the present work agree well with SEP baseline composition reported by McGuire *et al.* (1986) (listed as SEPB in Table 4) and other authors. The Fe/O ratio in events v and vi is significantly larger than the SEPB value (0.44 ± 0.05 and 0.95 ± 0.24, respectively, compared with 0.066 ± 0.006), and puts them into the "Fe-richest" class of observations defined by Meyer (1985). In the case of event vi, the Mg/O ratio is also enhanced by a factor ~2 compared with the SEPB value. It should be emphasized that neither of the events is ^{3}He-rich. A comparison of the abundances in events iva and v reveals a striking difference in iron-group composition between flare particles originating in the same active region, but associated with two different flare events. A similar effect has been reported in the case of the p/α ratio, which shows enhancements in successive SEP events from the same active region (Briggs *et al.*, 1979).

The energy spectra (as characterized by the oxygen spectral index) in the two "Fe-richest" events are substantially flatter than in the remaining events. This is shown in Fig. 5, where we have plotted the event-averaged spectral slope for oxygen vs the Fe/O ratio for the eight periods listed in Table 2. The points for the two shock-associated events are shown as filled triangles. These data tend to support the existence of an inverse correlation between the ratio Fe/O and spectral index, as reported by McGuire *et al.* (1986) and Van Hollebeke *et al.* (1985). Also of note in event vi is the He/O ratio of 173 ± 70. Even given the large statistical uncertainty, this ratio is high compared with the SEPB value of 53 ± 5. A similar result has been obtained in the case of the 3 June 1982 flare, for which a He/O ratio of 102 ± 14 was found (Van Hollebeke *et al.*, 1985).

The results shown in Fig. 5 are consistent with the suggestion of Reames (1988) and Reames *et al.* (1990) that the two classes of solar event that can be distinguished by differences in the X-ray properties of

TABLE 4. SEP ELEMENTAL ABUNDANCES (O = 1) : 4.25–8.5 MeV NUCLEON^{-1}

	SEPB	i	iia	iib	iii	iva	ivb	v	vi
He	53	73±6	64±7	88±10	82±9	57±6	79±2	54±7	173±70
C	0.45	0.57±0.05	0.38±0.05	0.49±0.06	0.65±0.08	0.56±0.05	0.47±0.02	0.43±0.05	0.42±0.13
N	0.13	0.20±0.03	0.11±0.02	0.15±0.03	0.17±0.03	0.15±0.02	0.15±0.01	0.15±0.03	—
O	1	≡1	≡1	≡1	≡1	≡1	≡1	≡1	≡1
Ne	0.13	0.13±0.02	0.10±0.02	0.16±0.04	0.22±0.05	0.11±0.02	0.13±0.01	0.19±0.03	0.15±0.07
Mg	0.18	0.20±0.03	0.20±0.04	0.20±0.04	0.14±0.04	0.21±0.03	0.19±0.01	0.21±0.03	0.43±0.14
Si	0.15	0.10±0.02	0.17±0.03	0.16±0.04	0.06±0.02	0.13±0.02	0.13±0.01	0.19±0.03	0.25±0.10
Fe	0.07	0.06±0.02	0.10±0.02	0.10±0.03	0.06±0.02	0.06±0.01	0.07±0.01	0.44±0.05	0.95±0.24
γ_O		−3.7	−3.0	−4.3	−3.8	−3.8	−4.2	−2.7	−1.3

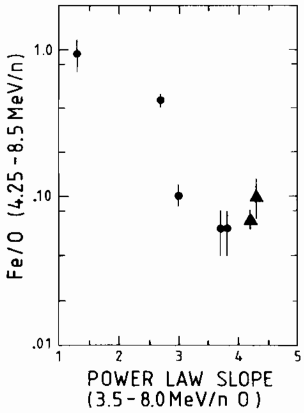

FIG. 5. SPECTRAL INDICES FOR OXYGEN VS RATIO Fe/O FOR THE SIX LARGE FLARE EVENTS (FILLED CIRCLES) AND TWO SHOCK-ASSOCIATED EVENTS (FILLED TRIANGLES).

the parent flare, namely impulsive (Class I) events and long-duration (Class II) events, produce particle populations with distinct heavy element abundances resulting from two different acceleration mechanisms. Fe-rich material is considered to be accelerated impulsively in the flash-phase of the flare, whereas low Fe/O ratios are thought to result from acceleration by large-scale shock waves propagating through the corona. The steep spectra associated with the *Phobos* 2 events having low Fe/O ratios are characteristic of shock-accelerated particles (Forman *et al.*, 1985). As pointed out by Reames *et al.* (1990), some mixing of these two populations is observed to occur, perhaps accounting for the intermediate value of spectral index seen in event v. The origin of the apparent positive correlation between He/O and Fe/O in event vi is not clear, but does not appear to be simply due to a rigidity-dependent process since the A/Z^* (Z^* = mean effective charge) ratios reported Gloeckler *et al.* (1981) for He and Fe are considerably different (2.06 and 4.15, respectively).

4.2. ^{3}He-*rich events*

Of the two ^{3}He-rich events studied, only event ii (1–3 October 1988) provided sufficient heavy-ion PHA events to allow us to determine the relative abundances of the individual elements C, O, Ne, Mg, Si and Fe. Our measured abundance ratios in this case show a significant enhancement for the $Z \geqslant 10$ species compared with the SEP baseline composition (by a factor ~3–4 for Ne, Mg and Si and ~14 for Fe). These results are in good agreement with the findings of Mason *et al.* (1986), who carried out a survey of

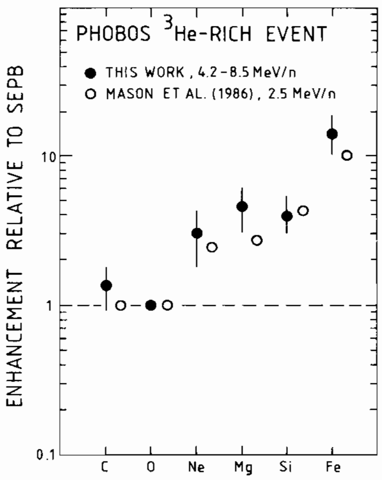

FIG. 6. ENHANCEMENT OF HEAVY ION ABUNDANCES RELATIVE TO SEP BASELINE (SEPB) COMPOSITION, AS DEFINED BY MCGUIRE *et al.* (1986), FOR THE ^{3}He-RICH EVENT OF 1–3 OCTOBER 1988.

66 ^{3}He-rich events. In Fig. 6 we plot the measured enhancement with respect to the SEPB composition for the October event. The ^{3}He-rich event of 8–10 September 1988 (event i of Table 3) also showed evidence for heavy-ion enhancement (Fe/O $\sim$ 1.5), although the statistics were too limited to permit a full analysis. Clearly, our sample of events is too small to enable us to examine the question of the origin of the heavy-ion enrichments associated with ^{3}He-rich events. If, as proposed by Mason *et al.* (1986), the enhancements are present in the coronal material *prior* to acceleration, this would represent a different situation than in the case of large flare events. Here, our results indicate that an acceleration mechanism may be responsible for the relative enhancements of heavy ions. The data presented here can only serve to underline the difficulties encountered in attempting to account for all aspects of SEP compositional variability by means of a single process.

4.3. *Shock events*

In an attempt to shed light on the origin of the energetic particles observed during shock-associated increases, we have examined the composition in events iib and ivb of Table 2, which show the steep spectra typical of shock-accelerated particles. The abundances measured in these events, also listed in Table 4, are, within the experimental uncertainties, very close to those of the solar flare particle population observed during the same period. This tends to support the hypothesis (e.g. Tan *et al.*, 1989) that the seed population for $\sim$several MeV nucleon^{-1} shock-accelerated ions is the ambient flare particles rather than solar wind ions.

5. CONCLUSIONS

We have studied the composition of energetic particles accelerated in solar flares using data from the LET experiment aboard the *Phobos* spacecraft. The abundances relative to oxygen measured in six large solar flare events occurring in the period July 1988 to March 1989 show the following features: (i) a large variability from event to event for $Z \geqslant 10$ ions, in particular Fe/O; and (ii) an apparent inverse correlation between the event-averaged spectral index and the Fe/O ratio. Although our results do not permit any firm conclusions concerning the source of the heavy-ion enrichment, they are consistent with a model in which Fe-rich material is accelerated impulsively at the flare, whereas events with lower Fe/O ratios result from large-scale coronal shock acceleration. The abundances measured in the two ^{3}He-rich events show enhancements in heavy ions relative to the SEPB composition comparable to those reported in previous studies. Our limited data set for this type of event does not enable us to draw conclusions regarding the source of the enhancement. Finally, our composition measurements for the two shock events indicate the ambient flare particles to be the seed population in the energy range of the LET.

Acknowledgements—The authors are indebted to numerous people for their contributions to the success of the experiment. In particular, from ESA/SSD, J. Henrion, L. Smit, J. M. Bouman, J. Fleur and R. Scheper; from MPAe, U. Strohmeyer, K. Fischer and W. Engelhardt; from CRIP, P. Rusznyak, A. Steiner, I. T. Szücs and L. Szabo; from IKI, S. Gubsky and V. Semenova. This work was supported in part by the German Bundesministerium für Forschung und Technologie.

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