SOLAR ENERGETIC PARTICLE COMPOSITION MEASUREMENTS IN INTERPLANETARY SPACE DURING THE RISING PHASE OF SOLAR CYCLE 22

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Abstract

We have measured the elemental composition of solar energetic particles (SEP) in the energy range $\sim 4 - 8.5$ MeV/nucleon during the rising phase of Solar Cycle 22 using data from the Low Energy Telescope (LET) instrument aboard the *Phobos 2* spacecraft. Three of the six solar flares included in the present study occurred during the period of high activity in March 1989 associated with Region 5395. 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 events, which includes two interplanetary shock-related increases, show an inverse relation to the spectral index of oxygen. This is in agreement with the findings of McGuire et al. [1] and Van Hollebeke et al. [2]. The abundances measured for the shock-associated events are consistent with the acceleration of the ambient population of solar flare particles.

1. Introduction The elemental composition of solar energetic particles has been the subject of many investigations over the past two decades (e.g. [1, 3] 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 may be understood as being primarily due to rigidity-dependent effects which operate at the time of SEP acceleration and/or propagation, and which introduce biases that act upon a baseline composition characteristic of ordinary coronal material [3]. On the other hand, there is strong evidence that additional effects complicate this rather simple picture, particularly in the case of He. In this paper we present preliminary results of a new study of SEP composition using data obtained with the Low Energy Telescope (LET) instrument aboard the *Phobos 2* spacecraft during its mission to Mars.

2. Instrumentation and Analysis The *Phobos 2* LET is a four-element solid-state detector telescope covering the energy ranges 0.9(4.1) – 3.8(12.2) MeV/n (2-parameter mode) and 3.8(12.2) – 19(75) MeV/n (3-parameter mode) for H(Fe) nuclei. On-board particle identification of groups of species is used to enhance the sample of rarer particles in the data stream (limited by telemetry to 2 pulse height analysed (PHA) events per minute). Count rate information is available for all particles stopping in the instrument, thereby permitting normalization of the PHA sample. The data used in

Table 1. Summary of SEP events

Event	Period Date/Time(UT)	Type	Flare	Phobos 2 posn. r(AU)*	$\alpha(°)$†
i	28 Aug 88/ 2245 – 01 Sep 88/ 2325	flare	M2/E90	1.07	0
iia	17 Dec 88/ 0105 – 18 Dec 88/ 0325	flare	1B/E37	1.45	30
iib	18 Dec 88/ 1440 – 19 Dec 88/ 1410	shock	–	1.45	30
iii	24 Dec 88/ 0105 – 27 Dec 88/ 0105	?	–	1.47	35
iva	08 Mar 89/ 0105 – 09 Mar 89/ 0925	flare	3B/E69	1.58	74
ivb	09 Mar 89/ 1125 – 11 Mar 89/ 0105	shock	–	1.58	74
v	11 Mar 89/ 0545 – 14 Mar 89/ 0945	flare	3B/E22	1.59	77
vi	24 Mar 89/ 0105 – 25 Mar 89/ 0025	flare	3B/W28	1.60	82

* heliocentric distance † angle w.r.t. sun-earth line (east)

this study are from the lower (single dE/dX *vs.* E) energy range of the LET. Further details concerning the instrument can be found in [4].

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. 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. Three of the six flares occurred during the period of very high activity in March 1989 associated with Region 5395. A detailed description of *Phobos 2* LET observations of the March flare events is given in [5]. 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. An overview of the periods analysed and event characteristics is given in Table 1.

4. Results and Discussion . The SEP abundances of He, C, N, O, Ne, Mg, Si and Fe relative to oxygen for the eight events are listed in Table 2. The results refer to the energy interval 4.25–8.5 MeV/n. Also given in Table 2 is the spectral index for

Table 2. SEP elemental abundances (O=1): 4.25–8.5 MeV/n

	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±.05	0.38±.05	0.49±.06	0.65±.08	0.56±.05	0.47±.02	0.43±.05	0.42±.13
N	0.13	0.20±.03	0.11±.02	0.15±.03	0.17±.03	0.15±.02	0.15±.01	0.15±.03	-
O	1	≡ 1	≡ 1	≡ 1	≡ 1	≡ 1	≡ 1	≡ 1	≡ 1
Ne	0.13	0.13±.02	0.10±.02	0.16±.04	0.22±.05	0.11±.02	0.13±.01	0.19±.03	0.15±.07
Mg	0.18	0.20±.03	0.20±.04	0.20±.04	0.14±.04	0.21±.03	0.19±.01	0.21±.03	0.43±.14
Si	0.15	0.10±.02	0.17±.03	0.16±.04	0.06±.02	0.13±.02	0.13±.01	0.19±.03	0.25±.10
Fe	0.07	0.06±.02	0.10±.02	0.10±.03	0.06±.02	0.06±.01	0.07±.01	0.44±.05	0.95±.24
γ_O		-3.7	-3.0	-4.3	-3.8	-3.8	-4.2	-2.7	-1.3

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. [1] (listed as SEPB in Table 2) 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 to 0.066±0.006), and puts them into the "Fe-richest" class of observations defined by Meyer [3]. In the case of event vi, the Mg/O ratio is also enhanced by a factor $\sim$ 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 [6].

The energy spectra (as characterised by the oxygen spectral index) in the two "Fe-richest" events are substantially flatter than in the remaining events. This is shown in fig. 1, where we have plotted the event-averaged spectral slope for oxygen versus the Fe/O ratio for the eight periods listed in Table 1. 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. [1] and Van Hollebeke et al. [2]. 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 [2].

Taking the correlation shown in fig. 1 at face value, our results imply that acceleration processes could play an important role in producing the observed event-to-event variability in SEP composition, in particular with respect to heavy ion enrichments. On the other hand, as pointed out by previous authors (e.g., [2, 3]), the apparent positive

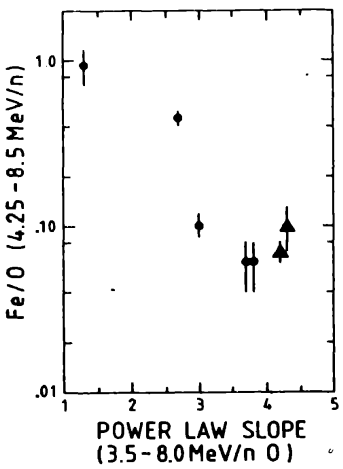

Figure 1. Spectral indices for oxygen vs. ratio Fe/O for the 6 flare events (filled circles) and 2 shock-associated events (filled triangles) used in this work.

correlation between He/O and Fe/O would argue against heavy ion enhancements being simply due to rigidity-dependent effects, since the observed A/Z* (Z* =mean effective charge) ratios for He and Fe are considerably different (2.06 and 4.15, respectively [7]). 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.

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, which show the steep spectra typical of shock-accelerated particles. The abundances measured in these events 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. [8]) that the seed population for $\sim$ several MeV/n shock-accelerated ions is the ambient flare particles rather than solar wind ions.

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