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ABSTRACT

We have performed a survey of energetic particle flux enhancements over the period October 1973 - December 1977 using the University of Maryland/Max-Planck-Institut ULET sensor on the IMP-8 spacecraft. During the four year period of the study, we find that the most extreme periods of Fe enrichment compared to oxygen were during solar flare events in February 1974 and May 1974. In these same events, the carbon abundance with respect to oxygen was significantly depleted when compared with a value C:O $\sim$ 0.45:1 for typical solar flares. These observations, taken together with previously reported ^{3}He enrichment in these events, give strong evidence for the importance of a wave-particle interaction in the pre-injection heating of the ambient matter.

Subject headings: abundances, solar - flares, solar, -
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I. INTRODUCTION

Experimental observations by a number of groups have established the existence of a class of small solar flares in which the few MeV/nucleon abundance of ^{3}He is greatly enhanced with respect to ^{4}He, occasionally with the ^{3}He:^{4}He ratio exceeding unity (e.g. Hsieh and Simpson 1970; Garrard, Stone and Vogt 1973; Hovestadt *et al*., 1975; Serlemitsos and Balasubrahmanyan 1975). Hurford *et al*. (1975) showed that many of the ^{3}He rich events were characterized by large abundances of $Z \geq 6$ particles compared with ^{1}H and ^{4}He, while Gloeckler *et al*. (1975), Hovestadt *et al*. (1975), and Anglin, Dietrich and Simpson (1977) established that the heavy nuclei enhancement was largely due to Fe. Although nuclear interactions at first seemed to offer an attractive explanation for the origin of the ^{3}He, the fact that flares with extremely large ^{3}He:^{4}He ratios had consistently low upper limits on other reaction products such as ^{2}H and ^{3}H, and were overabundant in heavy nuclei, posed serious problems for such models (for a recent review, see Ramaty *et al*. 1979). In this *Letter* we report a new feature of ^{3}He and Fe-rich events based on a detailed survey of the elemental composition of solar flare events spanning 4 years of continuous observations. For the most extreme examples of Fe-rich events, we find that the carbon abundance with respect to oxygen is significantly lower than the range of typical values in solar flares, and that in one event the carbon abundance is dramatically depleted.

II. EXPERIMENTAL OBSERVATIONS

The measurements reported here were carried out in interplanetary space using the University of Maryland/Max-Planck-Institut Ultra Low Energy Telescope (ULET) sensor on board the IMP-8 (*Explorer-50*) satellite. Since IMP-8 is in a roughly circular orbit at geocentric distances greater than 25 earth radii, the geomagnetic field has no significant effect on the spin averaged fluxes even at the rather low energies ($\sim$1 MeV/nucleon) reported here. The ULET sensor measures the nuclear charge and energy of an incident particle by the well-known dE/dx *versus* residual energy method. By the novel use of a thin window proportional counter as the dE/dx element, the telescope returns full two-parameter analysis of nuclei with energies >few hundred keV/nucleon (depending on the species) -- thereby making ULET an excellent instrument for composition studies at low energies (for a detailed description of the instrument, see Hovestadt and Vollmer 1971).

In order to establish a baseline in the search for unusual solar flare events, "box" sections of the instrument's dE/dx *versus* residual energy matrix were selected for various energy intervals for C, O and Fe. Daily average flux values (midnight to midnight GMT) were computed and plotted as shown in Figure 1. It was required that at least 8 counts (O + Fe) be observed in order to plot a point, leading to a threshold on the low flux side of the plot in Figure 1. Even at this threshold, the fluxes are more than 100 times higher than quiet-time values for the 1976-1977 period (Mason *et al*. 1977), thus excluding a number of very small Fe-rich and ^{3}He rich events from the survey (e.g., 30 November - 2 December 1974 period reported by Hovestadt *et al*. 1975). Note also that large solar flares and/or corotating events included in the figure may last several days, thus being represented by more than one point on the plot.

It can be seen from the figure that the composition variation is largest for the small events, as pointed out by Zwickl *et al*. (1978) in a survey of fluxes of H, He, $Z \geq 3$ and $Z \geq 20$ particles in solar flares. Furthermore, the largest Fe:O ratios ($\gtrsim$1) are seen to have occurred during the 1974 February 20-22 and 1974 May 9 events. Although the May 9 and 14 flux points are from two separate events, they appear to have both been associated with the same active region on the Sun (Hovestadt et al. 1975). A number of workers have previously reported Fe and ^{3}He enrichments during the February and May 1974 periods (for parent flare identifications and measured isotope ratios see review by Ramaty et al. 1979). The survey reported here establishes that these events showed the most extreme Fe enhancements over the four year period including the recent solar minimum, except possibly for events which were excluded in this study because of their small size.

In contrast to the enrichment of Fe, the survey plot of carbon *versus* oxygen reveals an extreme depletion of carbon during 20-21 February and 9 and 14 May 1974. (No cases of large carbon enhancement with respect to oxygen were found.) To determine the composition during these events more carefully, charge histograms were constructed of the ULET C, N, O region over the energy range 0.6 - 1.6 MeV/nucleon as shown in Figure 2. The data used in these histograms were summed over the duration of the flare particle event. Particle track locations in the dE/dx *versus* residual E matrix were accurately determined from the large number of counts analyzed during the large 1974 July 3-6 solar flare events. For the July 1974 data, although N is not resolved as a separate peak, examination of the histogram for the Z = 5 or Z = 9 peak locations shows clearly that N is present. In order to systematically estimate the abundances and associated errors in the sparsely populated histograms for the February and May 1974 periods, we performed maximum likelihood fits to the July 1974 data in order to accurately deduce the ULET response. Gaussian peak shapes for C, N and O, and a flat background were assumed, and the fitting program adjusted the peak locations, widths, and background level to deduce the best fit, which is shown as a curve drawn over the July 1974 histogram. Using the peak locations and widths deduced from the July 1974 data fit, maximum likelihood fits were performed on the February and May 1974 histograms where the number of counts in the C, N, O and background were varied. The number of counts of each type resulting from the fit is summarized in Table 1, where we also show the abundances relative to oxygen. In computing relative abundances and errors in Table 1, we have used the non-integer values for the most likely numbers of counts produced by the fitting procedure. Note that the number of background counts shown is for the entire histogram, that is, the integrated value over nuclear charge bits from 4.80 to 9.20, and that the size of the background relative to oxygen for the February and May 1974 periods is consistent with and no higher than that deduced for the July 1974 histogram fit.

The relative abundances resulting from the fit for the July 1974 event are in good agreement with somewhat higher energy measurements for this period (McGuire, von Rosenvinge and McDonald 1977). For the February and May 1974 events note that while the C:O ratio is low compared with typical values of $\sim$0.45 in solar flares, the N:O ratio is consistent with "normal" solar flare abundances. This singles out carbon as the element anomalously depleted. The table also shows previously reported values of the ^{3}He:^{4}He ratio during these periods, as well as the Fe abundance determined from the relative number of counts in the

"Fe box" of the dE/dx versus residual E matrix during these events. All three Fe-rich events show a carbon depletion: for the 20-21 February 1974 and the 8-11 May 1974 events the depletion compared with normal flares C:O ratios is at the 1-2 standard deviation level, and for the 14-15 May 1974 event the evidence for depletion is at greater than 5 standard deviations. Taken separately, the evidence for carbon depletion in the February 1974 and 8-11 May 1974 events is not conclusive. However, the fact that we observe evidence for such depletion in all the cases found for extreme Fe-enrichment, taken together with the very large carbon depletion in the 14-15 May 1974 flare, strongly suggests a general correlation between carbon depletion and the ^{3}He and Fe enrichments. The low C:O ratios during the 20-21 February and 8-11 May 1974 periods were apparent in our previous work (Hovestadt et al. 1975) in which we emphasized the ^{3}He and Fe enrichments for those flares. However, our first reports on the Fe abundance and ionization states of Fe, during the May 1974 period showed C:O ratios (primarily at lower energies than those given in table 1) which were consistent with normal solar abundances (Gloeckler et al. 1975, 1976). We have reexamined our analysis of those data points taking account of our more complete knowledge of instrument response and calibration with the now available large post-launch data base, and have concluded that the lower energy C:O data points in question were contaminated by nitrogen and very low energy Fe.

The major new points emerging for the present analysis are (a) the 4-year long survey which strongly suggests an association between carbon-depletion and ^{3}He and Fe enrichments, (b) the identification of "normal" N:O ratios during these periods, and (c) our detailed analysis of the 14-15 May 1974 event establishing an extremely low C:O ratio in that flare.

III. DISCUSSION

It would appear that models proposed for He enrichments by means of nuclear reactions (e.g. Ramaty and Kozlovsky 1974) or thermonuclear processes (Colgate, Audouze and Fowler 1977) could not yield simultaneously the anomalously low carbon-oxygen ratios we observe. Similarly, an acceleration model in which enhancement factors are organized by the 1st ionization potential, does not fit the C:O splitting taken together with our observed normal N abundance and enrichments in Fe. Indeed, to deplete the carbon abundance so dramatically compared to both nitrogen and oxygen appears difficult enough so that these new observations may provide important clues to the accelerating process and constraints on theories of solar cosmic rays. In particular, since C, N and O are virtually stripped of all their electrons at coronal temperatures greater than a few million degrees (Jordan 1969), it would seem that for these flares the initial temperatures must be low enough so that differences in ionization state (and thereby charge-to-mass ratio) can enter the process. These considerations favor, e.g., plasma wave heating models proposed for ^{3}He enrichments by Ibragimov and Kocharov (1977) and for simultaneous ^{3}He and Fe enrichments by Fisk (1978). In the case of the model of Fisk (1978), we note that for nitrogen or oxygen to have a charge-to-mass ratio favored by his preferential heating mechanism, temperatures as low as a few times 10^5 degrees--significantly lower than typical coronal temperatures--would be required. Thus, in order to include the favored charge-to-mass ratios in Fisk's model for O and Fe, heating of the plasma over a broad temperature range would be required in the pre-acceleration mechanism.

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Table 1

ABUNDANCE RATIOS

(0.6 - 1.6 MeV/Nucleon)

Category	20-21 Feb. 1974		8-11 May 1974		14-15 May 1974		3-6 July 1974	
	# counts observed	relative abundance	# counts observed	relative abundance	# counts observed	relative abundance	# counts observed	relative abundance
background*	5 ± 5	0.14 ± 0.14	3 ± 3	0.14 ± 0.14	11 ± 7	0.32 ± 0.21	2094 ± 124	0.37 ± 0.02
C	7 ± 3	0.20 ± 0.10	5 ± 3	0.24 ± 0.15	0^{+2}_{-0}	$0.01^{+0.07}_{-0.01}$	2145 ± 69	0.38 ± 0.01
N	9 ± 4	0.24 ± 0.11	7 ± 3	0.35 ± 0.20	4 ± 3	0.12 ± 0.10	1050 ± 55	0.19 ± 0.01
O	37 ± 7	1.	20 ± 5	1.	36 ± 7	1.	5656 ± 102	1.
Fe	76 ± 9	2.05 ± 0.44	68 ± 8	3.46 ± 0.95	93 ± 10	2.58 ± 0.57	2538 ± 50	0.45 ± 0.01
$^3He/^4He$		0.09†		1.06†		0.10 ± 0.05‡		

* total number of background counts between charge bins 4.80 - 9.20

† Hovestadt et al. (1975), for periods 2/20-23/74 and 5/7-13/74

‡ McGuire, McDonald and von Rosenvinge (1979), for 5/14/74 (quoted by Ramaty et al. 1979)

Figure 1 - Daily average flux values measured over the range 1.0 - 4.6 MeV/nucleon by the ULET sensor between 1973 October 30 and 1977 December 1. Points X: values on 20, 21, and 22 February 1974; points O: 9 and 14 May 1974.

Figure 2 - Charge histograms of ULET sensor C, N, O tracks taken during four selected time periods. Note changes in vertical scale. Curve superimposed on histogram for 3-6 July 1974 is maximum likelihood fit to the data (see text for details).

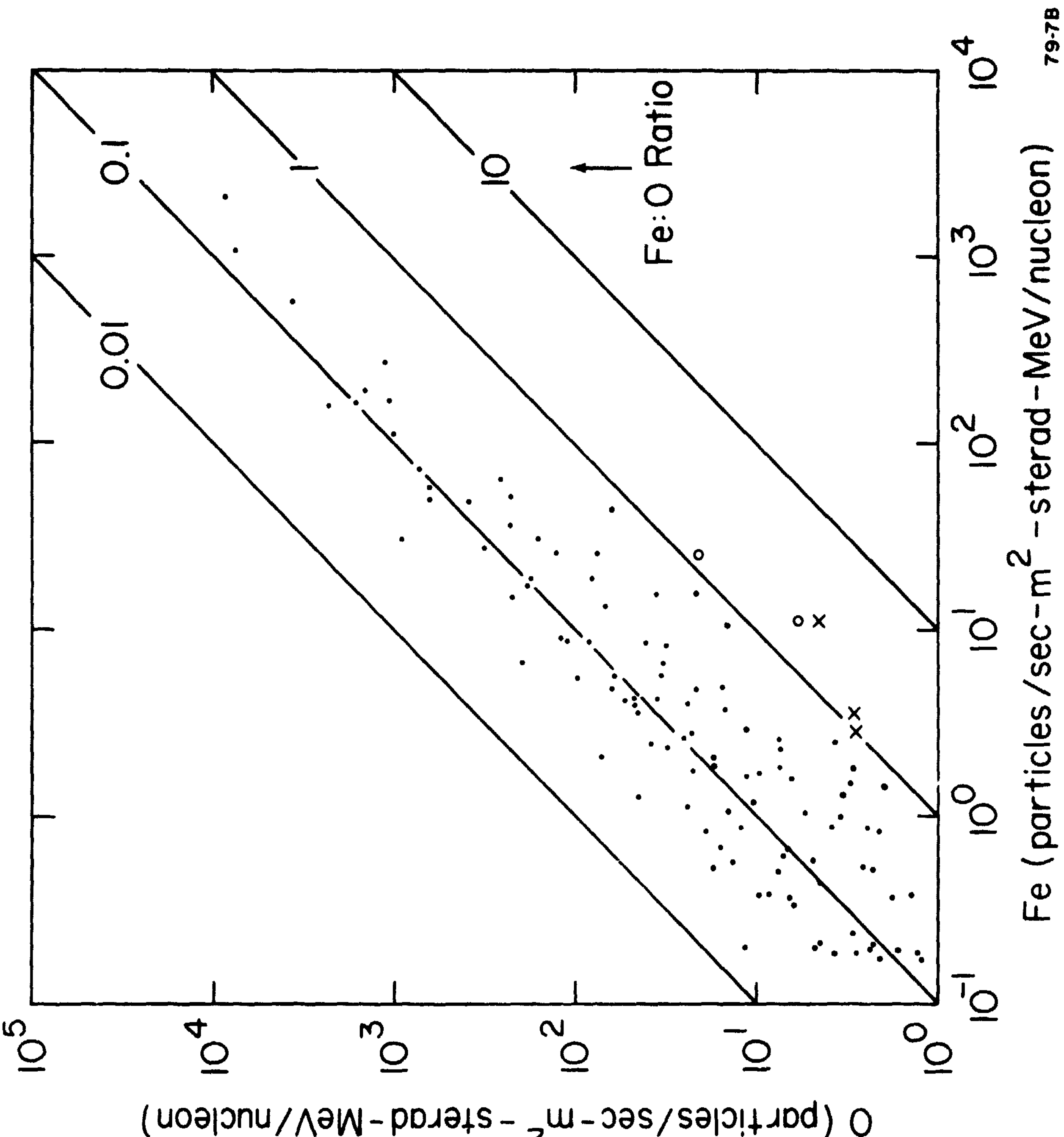
O (particles/sec-m^2-sterad-MeV/nucleon)
Fe (particles/sec-m^2-sterad-MeV/nucleon)
Fe:O Ratio
0.01
0.1
1
10
10^0
10^1
10^2
10^3
10^4
10^5
10^{-1}
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Figure 1

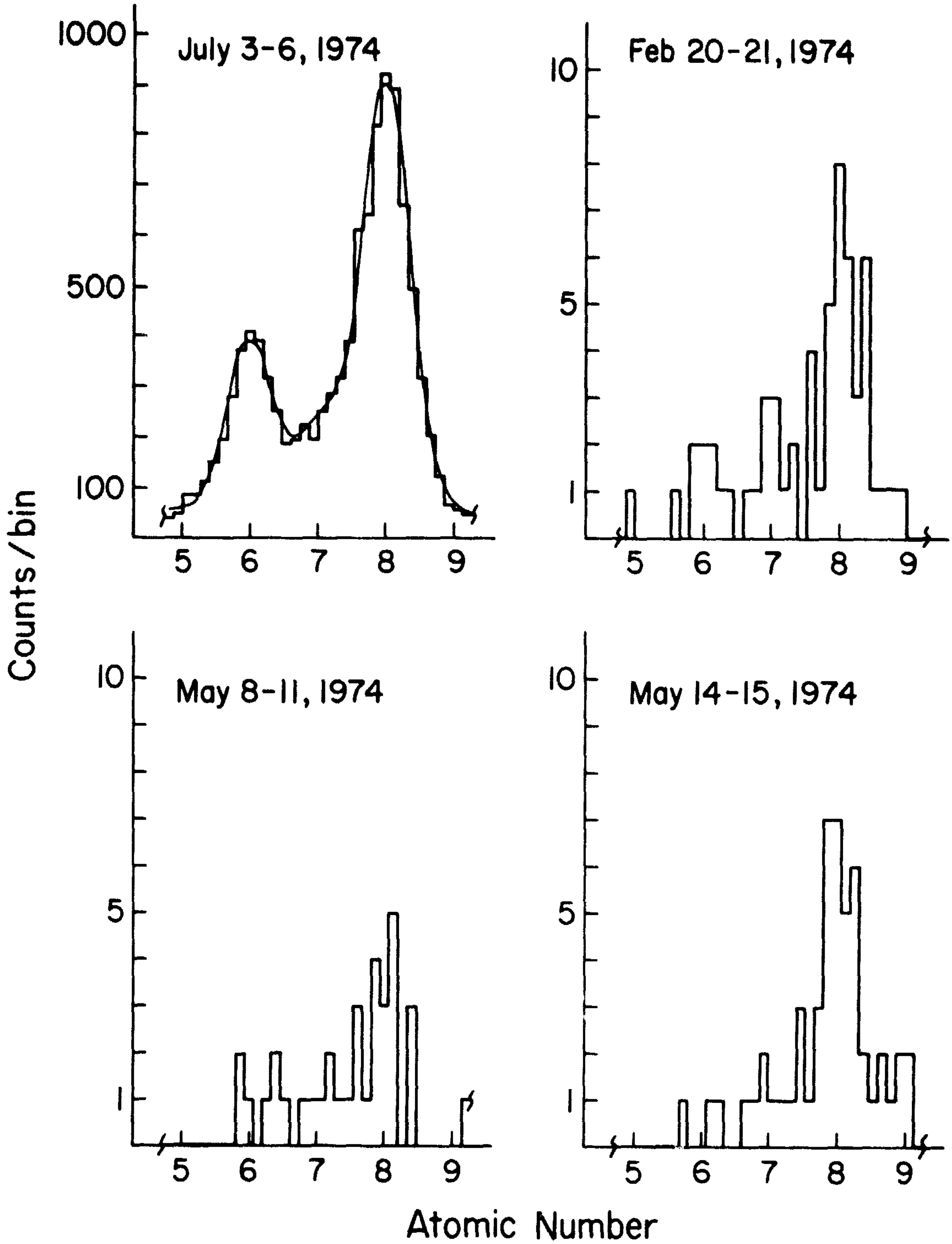

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Figure 2