ABUNDANCE VARIATIONS IN SOLAR ENERGETIC PARTICLES

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ABSTRACT

We have examined abundance variations in a large number of events including smaller non-impulsive events not previously considered. We find that whereas a comparison at equal energy per nucleon is appropriate for heavy ions this is not the case when including H. The best representation is either in terms of rigidity or energy per charge depending on the type of event under consideration. For the majority of large events, where particles are primarily accelerated at interplanetary shocks, if abundances relative to H are evaluated at equal energy per charge then abundance ratios are compatible with solar wind values and spectral shapes agree. Furthermore the behaviour of H is then compatible with that of other high FIP elements.

1. Introduction

In a previous study (Cane et al., 1991) we used data from our ISEE-3 experiment (von Rosenvinge et al, 1978) to examine abundances of heavy ions in large proton events. We showed that enhancements and depletions were reasonably well-ordered as a function of mass, except for ^{4}He which did not behave as expected. We showed that the greatest depletions of heavy ions occurred when particles were accelerated at interplanetary shocks. Enhancements of heavy ions usually occurred at event onset and we attributed them to the presence of flare-heated material. Our earlier study did not consider protons and, as noted above, the ^{4}He results were hard to interpret. The present study combines the ISEE-3 data with data from the Goddard Space Flight Center experiments on IMP-8 (McGuire et al., 1986) which are more suited to looking at H and ^{4}He. For the remainder of this paper when we use the term He it is ^{4}He that is implied.

2. Data Analysis

We studied two groups of events. One consisted of 81 events detected by IMP-8 during the period Nov. 1973 to Jan. 1989 for which He was measurable above 30 MeV/nuc. The other group consisted of 53 events detected by IMP-8 and ISEE-3 for which there was measurable O in the 7-12 MeV/nuc range. This covered the period Sep. 1978 to Apr. 1983. In all cases the particle increases were well-associated with a solar event. Forty-one events were common to both lists. Our study was based on event-averaged intensities.

From a study of the He/H ratio in a number of energy ranges it is clear that the ratio is very dependent on energy range and event size and there appear to be two groups of events. One group shows a very strong variation in the He/H ratio as a function of event size but little with energy whereas the other group shows a strong dependence on energy and little variation with event size. The most intense events belong to the second group. Figure 1 shows He/H ratios for the 4-6 and 43-63 MeV/nuc ranges. The abscissa is event size which is given by the H intensity in the 24-29 MeV range in units of particles/(cm^2 sec ster MeV). At the higher energy only events in the first group are apparent. Clearly spectral variations are involved. Spectral indices in two energy ranges

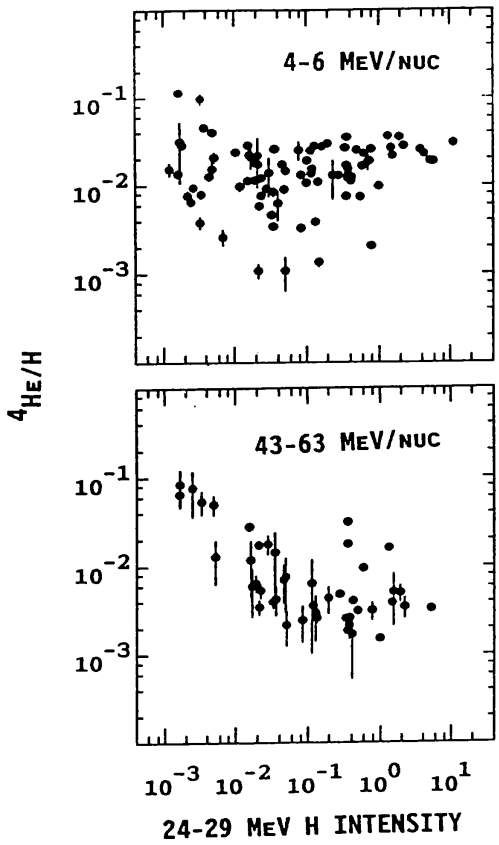

FIGURE 1

are shown in Figure 2. In Figure 2 we have indicated which events have intensities strongly influenced by interplanetary shocks. Events without local shock effects are shown with open circles. Filled circles indicate events with shocks and the size of the circle is a measure of the shock transit speed.

To understand these variations further we plotted the spectra as a function of rigidity and of energy per charge. The rigidity representation was very poor for the shock associated events, implying He/H ratios >1 and large variations as a function of rigidity. However for the events without local shock effects the rigidity representation was an improvement, leading to a more uniform distribution of He/H ratios. The energy per charge representation of the shock-associated events was a slight improvement over the energy per nucleon representation. For both groups of events the mean He/H ratio was about 0.05. Comparing He and H at equal energy per nucleon implies He/H ratios of about 0.01, as may be seen in Figure 1.

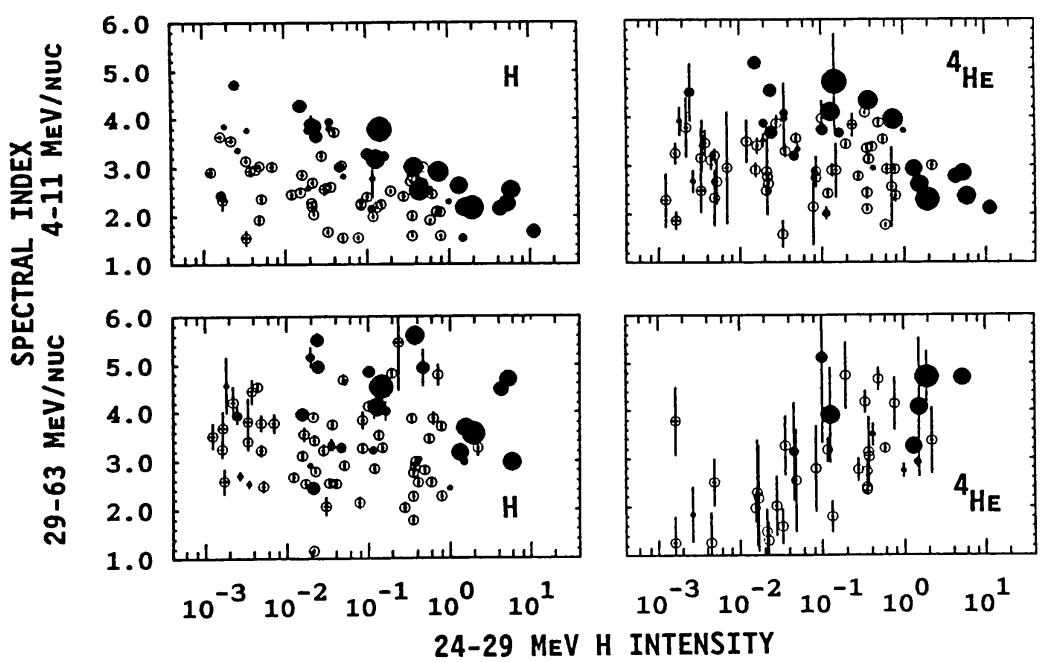

FIGURE 2

In order to extend the results to heavy ions we compared IMP-8 H intensities with ISEE-3 O intensities. Again we compared spectra in terms of energy/nucleon, energy/charge and rigidity. We considered O to have charge +7 based on observations of Luhn et al. (1985). We found the same result, namely that the best representation for intensities strongly influenced by interplanetary shocks was energy/charge rather than energy/nucleon. This is illustrated in Figure 3 for two events. The H/O ratios implied by the normalization factors used in Figure 3 are 1000 for energy/charge and 5000 for energy/nuc. There were few events where rigidity was a better representation and one of them is shown in Figure 4. In Figure 4 the implied H/O ratios are 1000 for rigidity and 5000 for energy/nuc.

We also compared O intensities with Fe intensities and found that energy/nuc was the best representation for all events, particularly in terms of the derived Fe/O ratios. However it should be noted that the Fe spectra were generally slightly steeper than the O spectra.

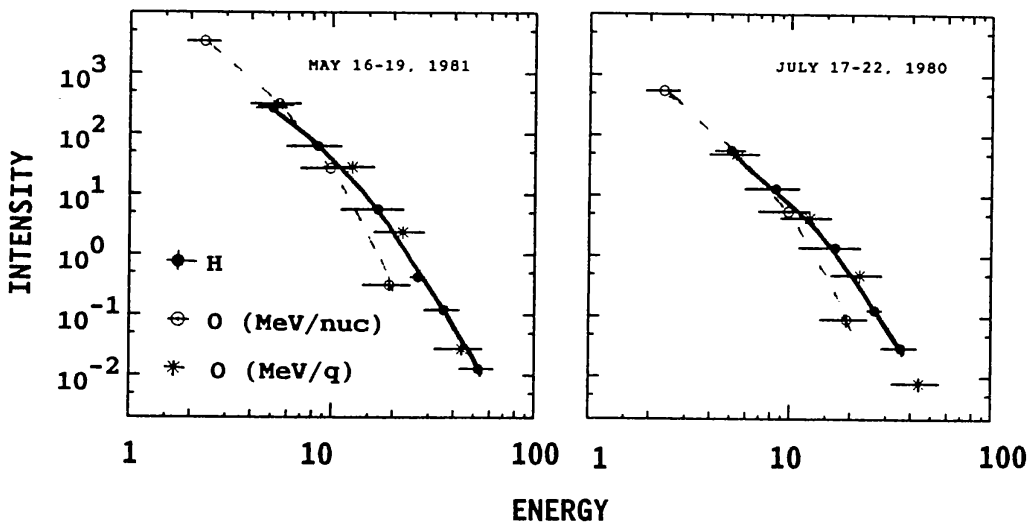

FIGURE 3

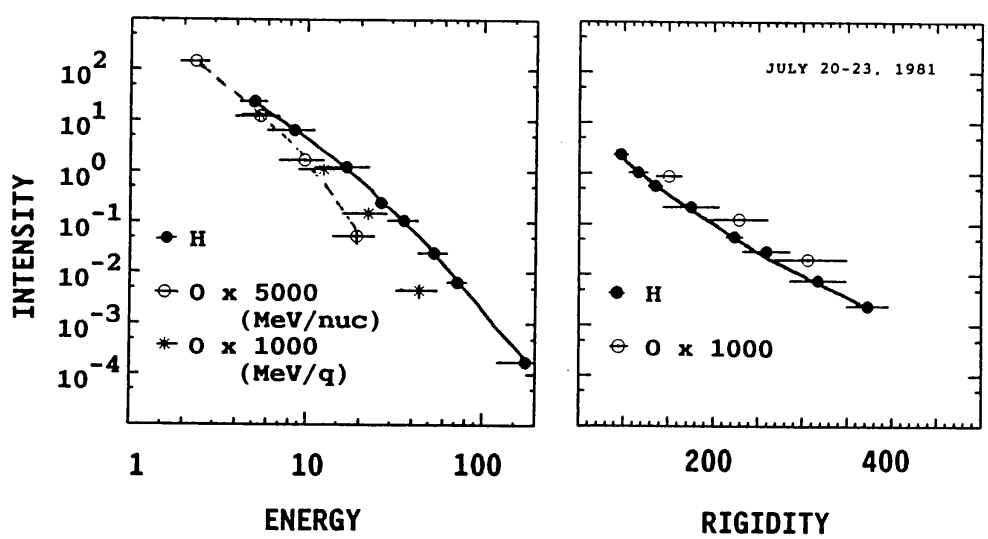

FIGURE 4

3. Discussion and Conclusions

We have found that abundances relative to H show less variability from event to event and as a function of energy if species are not compared at equal energy per nucleon but rather at equal rigidity for one group of events and at equal energy per charge for another group. Examination of the time histories of the events shows that the first group are those in which particles arrive promptly. Such events are well connected. Some less well-connected events behave the same way at high energies, typically above 60 MeV for H. For the majority of large events the intensities are strongly influenced by interplanetary shocks and these fall in the second group. These occur at all longitudes except close to the west limb.

By dividing the events in the above manner we find a He/H value of about 0.05 rather than 0.01, the value obtained when they are compared at equal energy/nuc. This former value is compatible with the mean He/H of the solar wind. We note that Lanzerotti and Maclennon (1973) pointed out this compatibility if He and H in SEPs were compared at equal energy per charge. We deduce that the events they studied were dominated by particles accelerated at interplanetary shocks since 3 of 7 were from the east limb (Cane et al., 1988). Likewise a H/O ratio of about 1000, as determined in this study, is similar to the solar wind and photospheric values. Note that this puts H on the same level as other high FIP elements when depletions relative to photospheric values are considered as a function of FIP.

For elements other than H, abundances are probably best determined by considering ions at equal energy per nucleon but this part of our study is incomplete. If this result holds we would interpret this to mean that acceleration at interplanetary shocks does not differentiate between ions with charge/mass of 0.5 or less.

It should be emphasized that depletions/enhancements of heavy ions have been shown to depend on charge/mass and there is an energy dependence (Cane et al., 1991). Consequently one might have expected that the energy/nuc representation for Fe and O would be appropriate. From the spectra it is not clear that it is and the Fe/O values are higher by about a factor of three than the value found for the solar wind.

References

Cane, H.V., Reames, D.V. and von Rosenvinge, T.T., J. Geophys. Res., 93, 9555, 1988.

Cane, H.V., Reames, D.V. and von Rosenvinge, T.T., Ap. J., 373, 675, 1991.

Lanzerotti, L.J. and Maclennan, C.G., J. Geophys. Res., 78, 3935, 1973.

Luhn, A. et al., Proc. 19th ICRC, 4, 241, 1985.

McGuire, R.E., von Rosenvinge, T.T., and McDonald, F.B., Ap. J., 301, 938, 1986.

von Rosenvinge, T.T., McDonald, F.B., Trainor, J.H., Van Hollebeke, M.A.I. and Fisk, L.A., IEEE Trans., GE-16, 208, 1978.