THE HEAVY ION COMPOSITION IN ^{3}He-RICH SOLAR FLARES

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1. Introduction. It has been known for some time that ^{3}He-rich flares show a tendency to be enriched in heavy ions (5), and that this enrichment covers the charge range through Fe (e.g. 3,8,10,14). The discovery of this association was responsible, in part, for the discarding of ^{3}He enrichment models which involved spallation or thermonuclear reactions, since such models were unable to produce heavy nuclei enhancements (e.g. review in ref. 12). More attractive appeared to be plasma resonance models which offered the possibility of producing ^{3}He and also heavy nucleus enrichments (e.g. 2,7). Previous studies of heavy nucleus enrichments in ^{3}He-rich flares (8,10) have covered only a few, isolated cases, thereby precluding the identification of systematic features of these enrichments. In order to investigate this association more thoroughly, we present here results of a survey of heavy nucleus abundances observed in 66 ^{3}He-rich flares which occurred over the period October 1978-June 1982.

2. Observations. The measurements were carried out in interplanetary space using instruments on the ISEE-3 spacecraft. ^{3}He and ^{4}He data are from the Goddard VLET sensors (13), and the heavy nuclei abundances are from the MPI/UMD ULEWAT sensor (4). The flares studied, and their method of selection, have been described in reference 6. In the present study, considerable care was exercised to insure that the two instruments were properly intercalibrated (9).

Figure 1 shows the enhancements relative to large flare abundances (from ref. 8) for 32 ^{3}He-rich flares in which there were ^{4}He flux increases. The energy ranges are 1.3-1.6 MeV/nuc for ^{4}He, and 1.0-1.8 MeV/nuc for heavier ions. Although the enhancements are normalized to 0, the choice is arbitrary, and it can be seen from the figure that the enrichment increases with A or Z over the entire range ^{4}He through Fe. Figure 1 includes data for three "carbon-poor" flares (8) and for a survey of 17 flares (10). Note the striking similarity of the enhancements reported in the three separate studies. Note also that the measurements in the figure cover the range 1-17 MeV/nuc, and that there is no evidence of an energy dependence in the abundance pattern--thus the composition appears to be a measure of the abundances in the pre-injection plasma, e.g. as in the model of Fisk (2).

The error bars for the new results in Figure 1 are not obtained from the averaging (as is the case in the earlier studies), but rather they show the range of values observed in 2/3 of the cases centered about the mean. Thus, the "1-sigma" errors in the present work give an idea of the spread of values observed over a number of flares.

In view of the large range of ^{3}He/^{4}He enrichments (from ~10^3 to >10^4 times coronal values), one of the most surprising results of this survey was the discovery of a relatively narrow range of heavy nuclei enrichments. This can be seen from Figure 2, which shows histograms formed by least-squares fitting of each of 44 flares to the

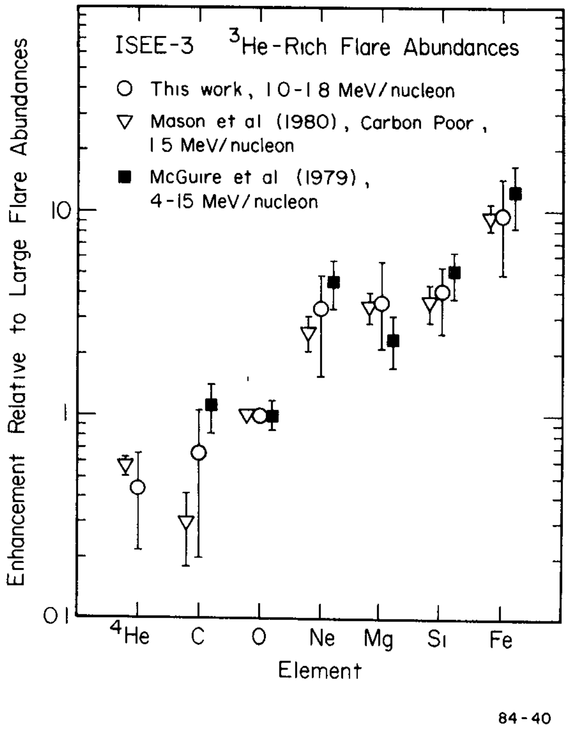

Figure 1

the abundance pattern shown in Fig. 1, and tallying the fractional deviations from the average values for each element. This fitting process results in histograms centered at 1.0, whose width is a measure of the deviations of individual elements from the average pattern (Fig. 1). Over the range C-Fe (left histogram) over 90% of the points fall within a factor of 2 of the mean, that is, between 0.5 and 2.0. Most of the large deviation points are from the element C, as can be seen from the right histogram, which shows fits over the range O-Fe, where 93% of the points fall within a factor of 2 of the mean.

If the heavy nucleus enrichment is caused by the same mechanism which causes the ^{3}He enrichments, then we might expect a ratio such as Fe/O to correlate with the ^{3}He/^{4}He ratio. Figure 3 shows that this is not the case: even though the Fe/O ratio is very large in these flares, the heavy least squares fit line in the figure has a slope of 0.02±0.06, and thus we find no statistically significant correlation between the degree of Fe enrichment and the degree of ^{3}He enrichment.

Flares showing extreme deviations from the average pattern may yield information about the acceleration mechanism(s). Therefore all the flares were examined for large χ^2 deviations from the average pattern. Only 4 of the 66 flares had significant deviations. The abundances in each of these is shown in Figure 4, where they are compared with large flare abundances (8) and the pattern from Fig. 1. Considering case (a) in the figure, the abundance anomaly is an enrichment of C by about 3 standard deviations compared with the ^{3}He-rich flare pattern. This is the most

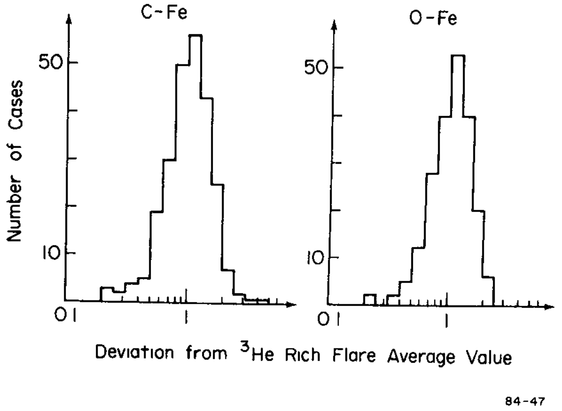

Figure 2

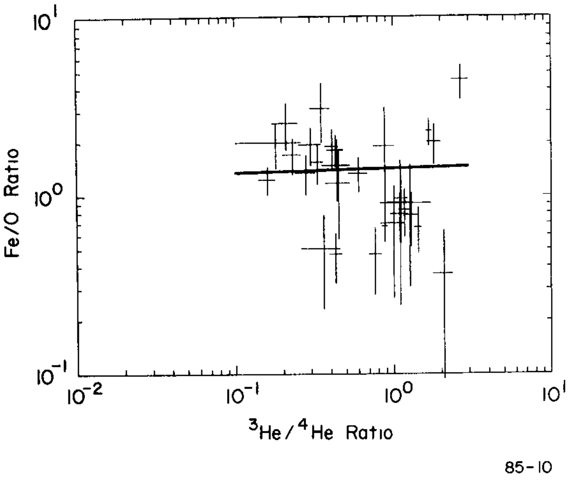

Figure 3

puzzling of the cases, and might be due to a statistical fluctuation. Case (b) appears to be an extreme example of the usual enhancement pattern. Cases (c) and (d) appear to show normal flare abundances for a range of lighter elements, and the ^{3}He-rich flare pattern for the remaining heavier elements. These latter cases are similar to the pattern seen in the 1977 Oct. 12-13 flare (8).

Perhaps the most important comments to be made about the search for deviations from the average pattern are: (1) such deviations are rather rare, and (2) when they occur, there is no trend for very large enhancements for single elements or limited ranges of elements.

3. Discussion. Figure 5 compares the heavy nucleus enrichment pattern observed here with predictions from several models. Panel (a) compares the present results with the calculations of ref. 7 for short (solid line) and long (dashed line) heating times. The fit is not particularly good, although a different set of model parameters might well improve it. Panel (b) shows a fit using a simple model (9) based on the Fisk mechanism. Although the fit in panel (b) is acceptable, it depends on a particular choice of plasma parameters which if varied slightly will produce an enhancement pattern quite different from the result in our survey. In general, the plasma resonance models appear to need a very special set of parameter choices to yield the observed enrichments, and this is unsatisfying in view of the fact that virtually the same pattern appears from one flare to the next.

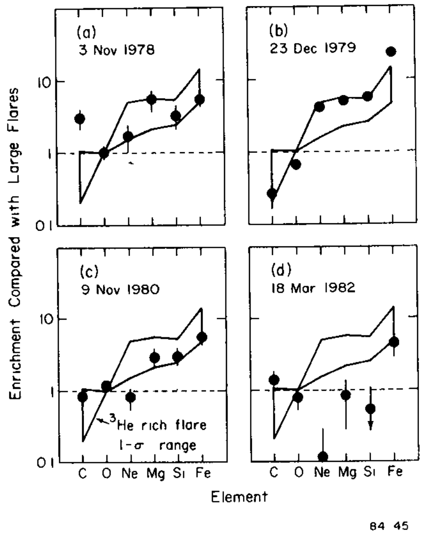

Figure 4

Figure 5(c) shows an enrichment pattern taken from the detailed calculations of Nakada (11) concerning the transport of heavy ions in the lower corona. Nakada's calculation includes effects of gravitational settling and thermal diffusion, assuming a temperature gradient of 1 K/cm at T = 10^5 K. The line in Fig. 5(c) shows the range of enrichments (compared with the baseline photospheric composition) for the range 5-9 x 10^5 K. The pattern is a surprisingly good fit to our results, and is all the more interesting because the mechanism in this case appears to produce basically the same result over a broad temperature range.

We interpret the observations presented here, along with previously reported work, to show that while a plasma resonance mechanism may account for the ^{3}He enrichments observed in these flares, this mechanism does not appear to be an attractive one for explaining the heavy nuclei enrichments that are associated with these events. Rather, we suggest that the heavy nuclei enrichments are due to heavy ion enrichments in the ambient plasma at the sites where the ^{3}He rich flares occur. We note that in plasma resonance models such as that of Fisk (2), a relatively high ^{4}He/H ratio is required, and the same mechanism which produces this enhancement might also produce the heavy nucleus enrichments. Model calculations by Nakada (11) indicate that sites with such enrichments may routinely occur in the corona.

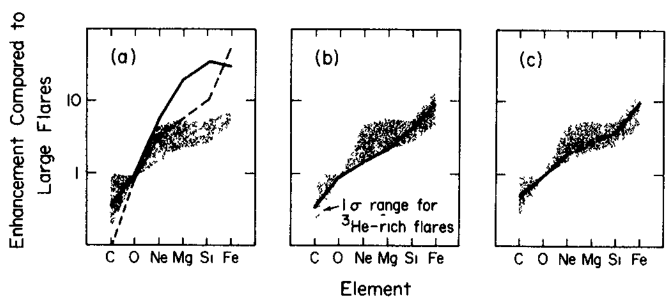

Figure 5. ^{3}He-rich flare heavy nuclei enhancements (shaded areas) vs. model calculations: (a) Kocharov and Orishchenko, (b) "Fisk", (c) lower coronal enhancements from Nakada (1969).

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