Measurements of ^{3}He and Heavy Elements in Impulsive SEP Events

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Abstract

The Solar Isotope Spectrometer (SIS), an instrument on board the Advanced Composition Explorer (ACE), measures solar energetic particle (SEP) elemental and isotopic abundances during solar events. During solar quiet times, SIS measures isotopes of low-energy cosmic rays from the Galaxy and isotopes of the anomalous cosmic ray component. The heavy element content at ∼10-20 MeV/nuc of two SEP events with large enhancements (>400x) of the ^{3}He/^{4}He ratio relative to coronal composition has been studied. We find heavy element abundance ratios which are consistent with those derived from past studies of ^{3}He-rich events within statistical limitations.

1 Introduction:

Solar energetic particles (SEPs) from impulsive solar events provide information about inherent source composition and particle acceleration mechanisms. Unlike large gradual SEP events, which are composed of solar wind material which has been accelerated by shocks formed by coronal mass ejections (CMEs) (Reames, 1998), impulsive SEP events are thought to contain particles which are accelerated from material at the base of the corona (Meyer, 1996). By studying a subset of these events which are rich in ^{3}He, one can identify characteristics which may provide insight into the underlying processes which drive the events.

Past measurements of composition in impulsive solar events have included a study of 228 ^{3}He-rich events in the 1.9-2.8 MeV/nuc energy region from the *ISEE 3* spacecraft from August, 1978 through April, 1991 (Reames et al., 1994), and measurements of a series of ^{3}He-rich events in the ∼1 MeV/nuc range in July, 1992 from the *SAMPEX* spacecraft (Mason et al., 1994).

SIS employs silicon solid state detector telescopes, with geometry factor ∼40 cm^{2}sr, and uses dE/dx vs. residual energy to calculate the mass and charge of incident particles. (Stone et al., 1998) The present mass resolution of SIS is ∼0.15- 0.3 amu, depending on nuclear charge and total energy. The energy range of SIS extends from ∼10 to ∼100 MeV/nuc. Because these energies are significantly higher than those of past measurements of ^{3}He-rich events, the available sample of events is necessarily different. The SIS spectrometer has detected approximately 10 events with ratios of ^{3}He/^{4}He exceeding ∼20% since ACE was launched in August, 1997. Of these events, 2 have significant abundances of heavy elements, including Ne, Mg, Si, and Fe, while the other 8 do not. These two events, which occurred on September 10, 1998 and May 28, 1998, will be the focus of this paper. Characteristics of the other ^{3}He-rich events are discussed by Wiedenbeck et al. (1999), while heavy ion composition in larger SEP events is presented by Cohen et al. (1999) and Leske et al. (1999).

2 Data Analysis:

Figure 1 depicts neon, magnesium, silicon, iron, and carbon to oxygen ratio enhancements, relative to coronal values extracted from 49 gradual SEP events (Reames, 1998), for the two ^{3}He-rich events occurring on September 10-12, 1998 and May 28-June 1, 1998. From the figure, it is clear that the carbon to oxygen ratio is close to its coronal value, while the abundance ratios Ne/O, Mg/O, Si/O, and Fe/O are enhanced by factors of up to ∼3.5. The galactic cosmic ray and anomalous cosmic ray spectra have been subtracted from the data. These background spectra were measured over 165 days of solar quiet time, from August 27, 1997 through March 23, 1998.

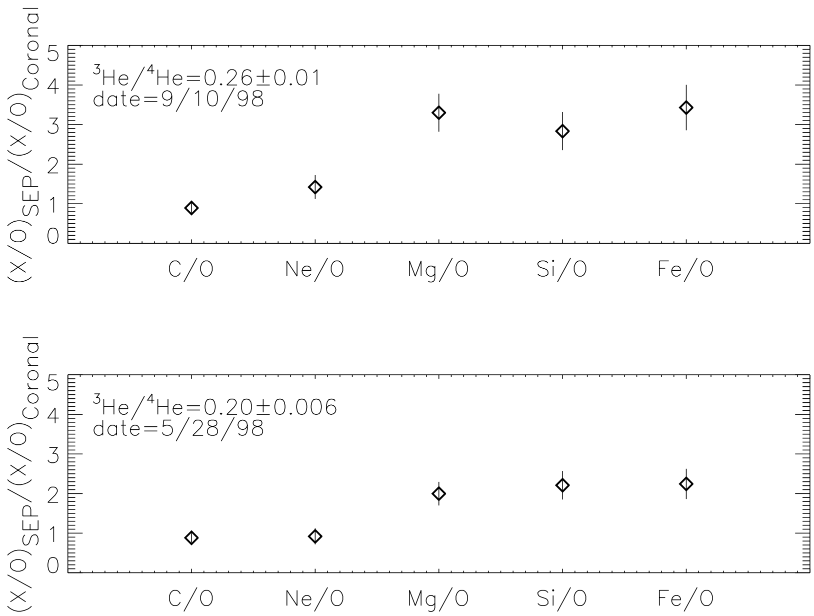

Figure 1: Heavy element and carbon to oxygen ratios (10-20 MeV/nuc) for the two ^{3}He-rich events occurring on September 10-12, 1998 and May 28-June 1, 1998.

For the two ^{3}-rich events, the regression slopes of six elements/C have been calculated with respect to Fe/C, and have been compared to the values obtained by Reames et al. (1994) in the right panel of Fig. 2. As an example, the left panel of Fig. 2 shows the Ne/C ratio plotted against Fe/C as measured by SIS for the two ^{3}He-rich events, and by ISEE 3 for the average of 228 ^{3}He-rich events. The regression slope calculated by Reames et al. (1994) is shown as the bold line, with their 2σ limits denoted by the dashed lines.

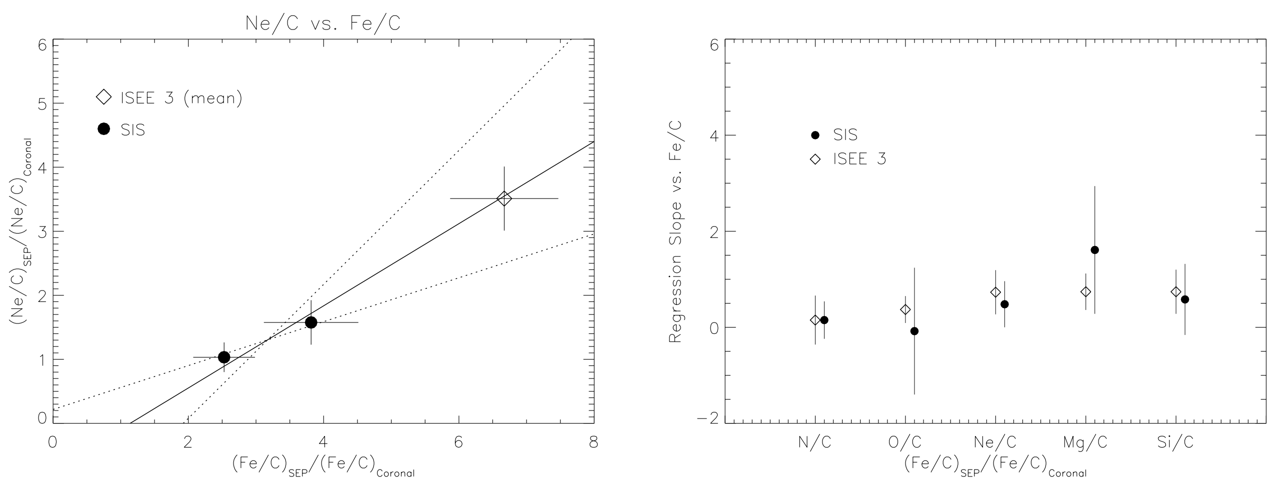

Figure 2: Left panel: Neon to carbon ratio, plotted against the iron to carbon ratio, for the two impulsive events which show significant heavy element abundances. The solid line is the regression slope calculated in (Reames et al., 1994), with the 2σ uncertainty shown as the dashed lines. Right panel: Slopes of regression between abundance ratios of five elements to carbon, and iron to carbon.

Uncertainties on the regression slopes in Fig. 2 have been determined through standard theory of propaga-

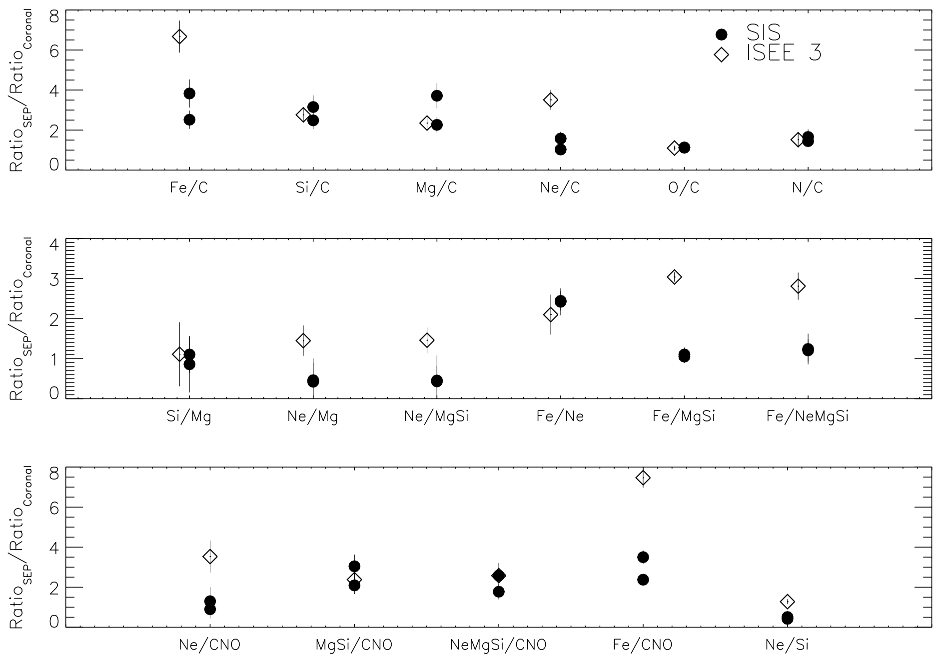

Figure 3: Abundance ratios measured by SIS during the two ^{3}He-rich events, normalized to their coronal values and compared with those obtained by Reames et al. Uncertainties on the SIS data points are $\pm 1\sigma$ of statistical error, while uncertainties on the ISEE 3 are $\pm 2\sigma$ of non-statistical population spread.

tion of error. These values have been compared to those obtained by employing the algorithm used by Reames et al. The method is as follows: Effective uncertainties on each data point include contributions from both the horizontal and vertical directions. The two components of the error are combined, such that the uncertainty is equal to the distance from the data point to the point on its error "ellipse" at which a line parallel to the regression line is tangent to the ellipse. The distance from the data point to the regression line is measured along the same direction. The slope of the regression line which causes a unit increase in χ^2 represents the 1σ uncertainty. Results for this method of uncertainty calculation and from the theory of propagation of errors are similar.

Because the data sample is limited to two points, it is not necessary to adjust the uncertainties for a non-statistical "population" spread, as discussed in Reames et al. (1994). All uncertainties calculated in this paper are purely statistical in nature.

3 Results and Discussion:

Although the SIS data sample of ^{3}He-rich events with measurable $Z>2$ is still very limited, indications from the two events reported here are that at energies of 10-20 MeV/nuc, the enhancement characteristics appear similar to those found by Reames et al. (1994) for a large set of events at $\sim$2-3 MeV/nuc.

Because C is not selectively accelerated in impulsive solar events, it is convenient to normalize abundances of other elements to it. Figure 3 shows that the Fe/C ratio is enhanced by a factor of $\sim$3, compared to $\sim$7 in Reames et al. (1994). The results also show that the O/C ratio is almost consistent with its coronal value, while N/C appears to be slightly enhanced by a factor of $\sim$1.7, both of which are consistent with Reames et al. (1994). In addition, the range of most abundance ratios shown in Fig. 3 start at or above coronal values. This suggests that impulsive SEP events originate in a gas which has coronal, and not photospheric, composition (Reames et al., 1994).

The behavior of elements in the Ne, Mg, Si group is also instructive. The value of Si/Mg measured here is consistent with its coronal value, a conclusion of the 1994 study. Consequently, the 1994 study found that Mg and Si behave identically in impulsive SEP events; this is borne out by the similarity between the Ne/Mg and Ne/Si ratios in Fig. 3.

A possible difference between these results and the Reames et al. (1994) study may occur with the Fe and Ne enhancements. The 1994 study found an average ratio of Fe/CNO to be $\sim$7 times its coronal value; here the Fe/CNO enhancement is $\sim$3. However, approximately 15% of the events from the 1994 study showed an enhancment of Fe/CNO of less than 3. Likewise, the Ne/CNO enhancement in the two SIS events is close to its coronal value, with an enhancement factor of $\sim$1.1, while the 1994 study found an enhancement of $\sim$3.5. A simultaneous study by Cohen et al. (1999), which involves heavy-ion rich events with lesser enhanced ($<$0.1) ^{3}He/^{4}He ratios, finds that the abundance ratios of Ne/C and Fe/C at 12-60 MeV/nuc are in accordance with those found by Reames et al. (1994). While the discrepancies between the results in this paper and the others mentioned above are interesting, more ^{3}He-rich events must be observed in the SIS energy range before a statistically significant comparison can be made.

Although it is difficult to make generalizations based on the small SIS data set, there have been many consistent noteworthy features between these data and past studies. A possible discrepancy occurs with the enhancement factors of Ne and Fe. If this trend were to persist with higher statistics at energies $>$10 MeV/nuc, it could be indicative of a source gas temperature which is greater than the 3-5 MK postulated by Reames et al. for ^{3}He-rich events. Meyer states that a relatively small enhancement factor for Ne relative to Mg and Si is suggestive of a source gas temperature which is greater than 5 MK. Cohen et al. (1999) also find that the high deduced charge states of Fe in events with small ^{3}He enhancements are indicative of hotter source gas temperature. Conversely, the lower limit on source gas temperature of 2.5 MK (Meyer, 1996) is supported in the SIS data by the lack of O/C enhancement. Finally, it is important to recognize that more studies of ^{3}He-rich events at these energies are required before reliable conclusions can be drawn.

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