The Isotopic Composition of Solar Energetic Particles

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Abstract. Since the launch of ACE in August 1997, the Solar Isotope Spectrometer (SIS) has observed 11 large solar particle events in which elemental and isotopic composition was determined over a large energy range. The composition of these events has raised many issues and challenged generally accepted characterizations of solar energetic particle (SEP) events. In particular, ^{3}He/^{4}He enhancements have been observed in several large events as well as enhancements of heavy ions typically associated with smaller impulsive events. The isotopic composition varies substantially from event to event (a factor of 3 for ^{22}Ne/^{20}Ne) with enhancements and depletions that are generally correlated with elemental composition. This correlation suggests that the isotopic enhancements may be related to the Q/M fractionation typically evident in the elemental composition of SEP events. However, there are also significant deviations from this pattern, which may imply that wave-particle resonances or other mass fractionation processes may be involved. We review the recent isotopic observations made with ACE and discuss their implications for particle acceleration and transport.

INTRODUCTION

One of the windows into the composition of the Sun's atmosphere is solar energetic particle (SEP) events. Measuring the composition of these events provides information regarding the particle source as well as acceleration and transport processes which can alter the initial composition. Understanding these processes furthers our knowledge of solar dynamics and allows SEP event composition to be used as a probe of solar composition.

Although there are event-to-event variations, SEP events generally can be classified into one of two categories, gradual or impulsive (1). Gradual events are large events that usually last for days. On average the composition is very similar to that of the solar wind and solar corona. This and the observed correlation between gradual events and coronal mass ejections (CMEs) has led to the conclusion that these particles are accelerated out of the outer corona and interplanetary medium by the interplanetary shocks that are sometimes formed by outwardly moving CMEs. Since typically the shocks are spatially large structures, the resulting SEPs can be observed over a broad longitudinal range.

Impulsive events are short in duration (usually hours) and have composition that differs substantially from that of the solar wind. Dramatic enhancements of ^{3}He have been observed, sometimes as great as 10^4 times that of the solar wind. The heavy ion composition is quite different from that of the gradual events; Ne, Mg, and Si are often enhanced by a factor of ~3 (normalized to C, N, and O) and Fe is typically enhanced by a factor of ~10 over average gradual event values. The correlation with optical and x-ray solar flares and the limited solar longitude range that these events originate from suggests that the sources of these particles are the solar flare sites themselves.

Within the two classes, the event-to-event variation can be substantial and is most likely a result of acceleration and/or transport processes. When compared to a multi-event average, both Fe-poor and Fe-rich gradual events have been observed. Often the

CP528, *Acceleration and Transport of Energetic Particles Observed in the Heliosphere: ACE 2000 Symposium,* edited by Richard A. Mewaldt, et al.

deviation in composition of a single gradual event from the long-term average composition can be well represented by a power law in charge/mass (Q/M) (2).

While the heavy ion composition of impulsive events varies by less than a factor of 2 (3), the $^3He/^4He$ ratio can vary by orders of magnitude from one event to another. The large enhancements of ^3He have been attributed to a resonance between the particles and ion cyclotron waves (4,5). This same mechanism has been suggested as a cause of the enhanced $^{22}Ne/^{20}Ne$ values observed in impulsive events (6). In this case, the particles would be resonating with the waves at the second harmonic of the ion cyclotron frequency (7).

Although there have been previous reports of events with both impulsive and gradual characteristics (e.g. 8), such events were considered anomalous. However, data from a new generation of energetic particle detectors have found a large fraction of long duration events that appear to have a mixture of impulsive and gradual characteristics (9,10) indicating that such events are not rare and need to be understood. Several large events have been observed which have significant enhancements of $^3He/^4He$ and Fe/O ~ 1 at energies ≥ 1 MeV/nucleon (9,10). Coronal mass ejections were often observed in conjunction with these events, typical of gradual events, yet the measured elemental and isotopic composition is more similar to that of impulsive events than gradual events (9,10) and the observed charge state composition includes charge states characteristic of impulsive events as well as those from gradual events (11).

Recently, observations of finite enhancements of ^3He over the solar wind value during time periods of

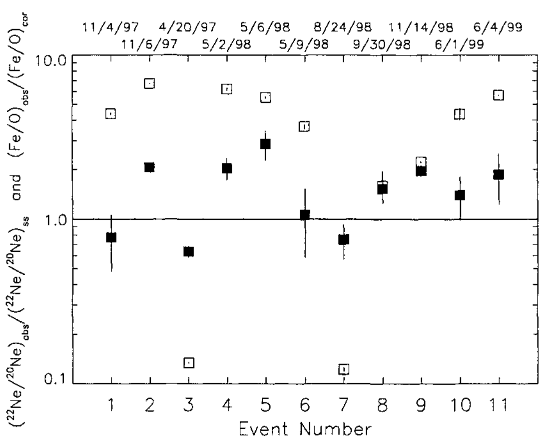

FIGURE 1. Enhancements of $^{22}Ne/^{20}Ne$ (filled symbols) and Fe/O (open symbols), relative to solar system (14) and gradual SEP values (1), respectively, for the 11 events measured by SIS.

low to moderate solar activity have prompted the suggestion that the enhancements of ^3He measured in these large SEP events may result from a re-acceleration of remnant impulsive material that is present in the interplanetary medium (10). It is further suggested that this may also account for the 'mixed' charge state composition of these events.

With new data from instruments with improved resolution and sensitivity it is becoming clear that the composition of SEP events deserves more examination. The event-to-event variation in elemental and isotopic composition provides clues to the acceleration and transport processes involved. In this study we review the recent composition measurements taken at ~10 – 60 MeV/nucleon in 11 large SEP events and the observed deviations from classic gradual event composition. These variations are examined in relation to the ideas of Q/M fractionation, wave-particle resonance, and the presence of remnant impulsive material.

OBSERVATIONS AND THEORIES

The data presented here were obtained from the Solar Isotope Spectrometer (SIS) (12) on the Advanced Composition Explorer (ACE). The instrument contains two telescopes, each composed of two position-sensing matrix detectors, followed by a stack of large-area silicon solid-state detectors. Using the standard ΔE versus residual energy technique, the nuclear charge, mass, and kinetic energy of the particles can be determined. The mass resolution of SIS allows the isotopes of elements of $2 \leq Z \leq 28$ to be resolved, while the large geometry factor permits this to be accomplished with excellent statistical accuracy.

Since the launch of ACE, 11 large SEP events have been observed and studied with SIS. The compositional variation between these events is dramatic, with $^{22}Ne/^{20}Ne$ ranging from 0.056 ± 0.014 to 0.212 ± 0.044 (13) and Fe/O ranging from 0.018 ± 0.001 to 0.900 ± 0.006 (9). As can be seen from Figure 1, the $^{22}Ne/^{20}Ne$ and Fe/O ratios, relative to solar system (14) and gradual SEP event values (1) respectively, vary substantially from event to event and are significantly enhanced in many of the events. Other elemental and isotopic ratios also show comparably large fractionation for these events (see 15,9,16).

In many of these events a significant overabundance of ^3He was measured (9,10). Mass histograms for each event are presented in Figure 2

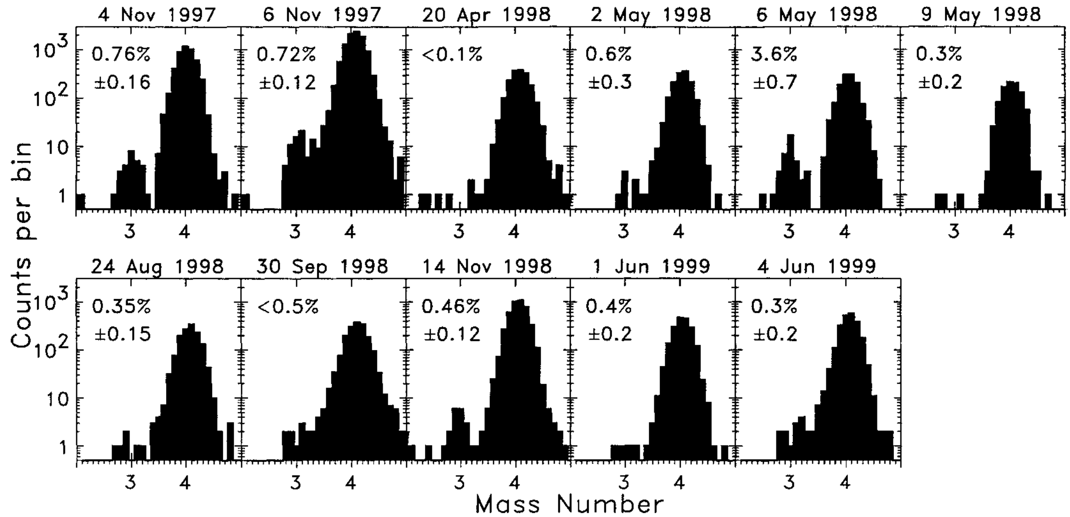

FIGURE 2. Mass histograms of 7.3 to 9.7 MeV/nucleon He for the 11 SEP events (16, copyright Astronomical Society of the Pacific 2000). Event average ^{3}He/^{4}He ratios are indicated for each period.

along with the ^{3}He/^{4}He ratio. In at least 4 events, the ^{3}He/^{4}He ratio is clearly enhanced by more than an order of magnitude above the solar wind value of 0.04% (17), and in most of the remaining events significant enhancements are also possible. Neither this nor the large heavy ion enhancements are expected for gradual events, suggesting either a mixture of impulsive and gradual material or significant fractionation during acceleration and/or transport.

Fractionation Theories

The Q/M fractionation process identified in (2) can produce elemental and isotopic enhancements. Assuming the fractionation can be expressed as a power law in Q/M, the measured abundance can be related to the source abundance as follows:

$$N_{SEP} = N_{Source}\left(\frac{Q}{M}\right)^{\gamma} \qquad (1)$$

If two isotopes have the same charge state then equation (1) reduces to a mass fractionation in the measured isotopic ratio:

$$\left(\frac{N_{M1}}{N_{M2}}\right)_{SEP} = \left(\frac{N_{M1}}{N_{M2}}\right)_{Source}\left(\frac{M_2}{M_1}\right)^{\gamma} \qquad (2)$$

If the same process is responsible for both the observed elemental and isotopic fractionations then they should be correlated. This is the case for species heavier than He and it has been reported that time periods with large ^{22}Ne/^{20}Ne enhancements also generally have large Fe/O enhancements (13), which is also evident in Figure 1. Since the Fe/O ratio also depends on the first-ionization-potential (FIP)-related fractionation, and the degree of FIP fractionation varies from event to event (18,19,20), the correlation is not as tight as might be expected. In addition, the power law behavior of the Q/M fractionation may not continue over the large Q/M range from Ne (Q/M ~ 0.4) to Fe (Q/M ~ 0.25).

A better correlation is found between the ^{22}Ne/^{20}Ne and the Na/Mg abundance ratios (21). Here the Q/M values of Na and Mg are similar to that of Ne and are relatively insensitive to temperature in the 2-5 x 10^6 K range due to the He-like electron configuration of the ions (22,23). Additionally, Na and Mg are both low-FIP elements, so the variation of the FIP fractionation is not an issue. Under the assumption that a power law Q/M fractionation is responsible for both the elemental and isotopic fractionation, we have investigated the degree to which this fractionation process represents the composition of the 11 events using the following three simple models.

A source population is created with elemental and isotopic composition as given in (1) and (14) and a charge state distribution determined from thermal equilibrium at a specified temperature as given in (22) and (23). The abundance of each ion is multiplied by an enhancement factor of $A(Q/M)^{\gamma}$. The resulting population is compared to the measured composition of an event and a χ^2 value is determined from

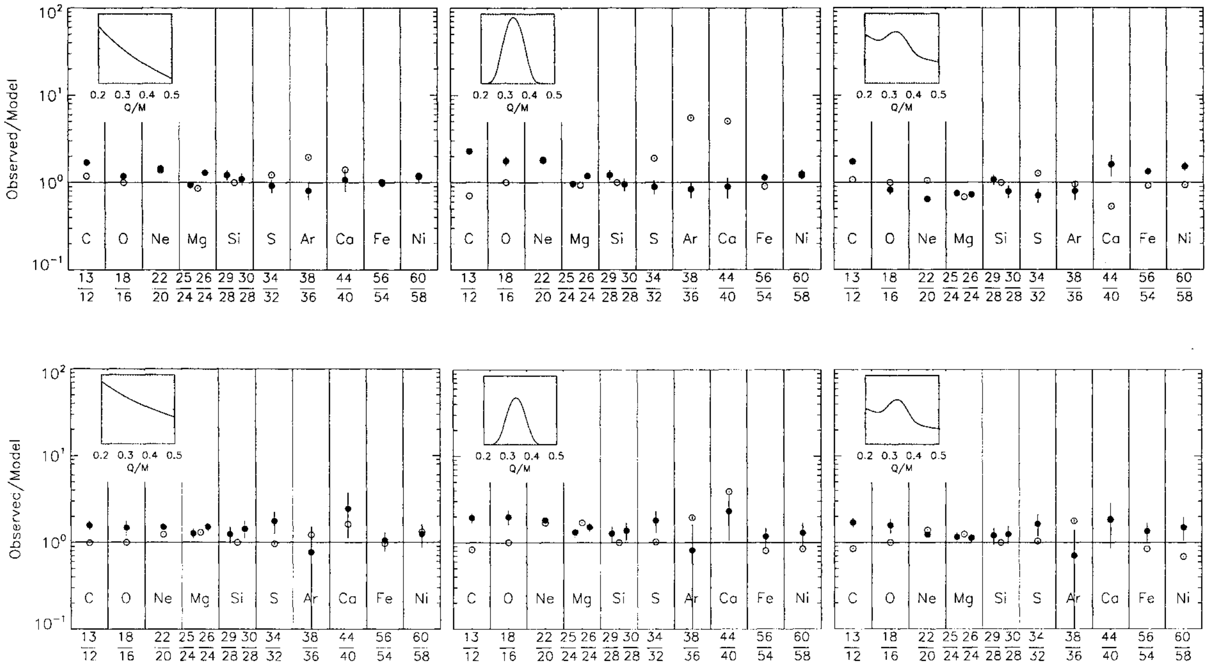

FIGURE 3. Results of the 3 models divided by measured ratios. Solid points are isotope ratios; open points are elemental ratios; inset graph shows the form of the enhancement function in arbitrary units. The top row shows data from the 11/6/97 event, the bottom row contains data from the 11/14/98 event. A perfect fit would result in points forming a horizontal line at 1.

$$\chi^2 = \sum \left(\frac{\frac{R_{Obs}}{R_{Mod}} - 1}{\frac{\sigma_{Obs}}{R_{Mod}}} \right)^2 \qquad (3)$$

where, R_{Obs} is the observed composition relative to that of average gradual events, R_{Mod} is the ratio resulting from the model, and σ_{Obs} is the uncertainty in the measurements. The model parameters, A, γ and the source temperature, are varied until χ^2 is minimized.

The fact that $^3He/^4He$ ratio is significantly enriched in some of these events relative to the solar wind suggests a wave-particle resonance may be operating during the acceleration of these ions. This can result in the enhancement of heavy ions with Q/M values near 0.333, those resonating with the second harmonic of the ion cyclotron frequency (7). This effect is investigated using a similar model to the one described above, but instead of a power law the enhancement factor is taken to be a Gaussian in Q/M with the peak at 0.333 and a standard deviation of 0.03. The choice of this standard deviation was based on a discussion of Q/M values expected to be affected by the resonance (7). The amplitude of the Gaussian and the source temperature are the fit parameters in this model. Since it is possible that both the Q/M and resonance processes are operating, a final version of the model uses the product of the Q/M power law and the Gaussian as the enhancement factor. In this case, the parameters are γ, an overall amplitude of the enhancement factor at Q/M = 0.333, and the source temperature.

The results of the models for the 3 different enhancement functions are given in Figure 3 for two events which have the best statistical accuracy, 6 November 1997 and 14 November 1998. It is evident that the resonance enhancement function alone (middle panel of both rows of Figure 3) does not yield results consistent with the SIS data. The best fit result still has extremely large inconsistencies in both the elemental (e.g., Ar/Si and Ca/Si) and isotopic (e.g., $^{13}C/^{12}C$, $^{18}O/^{16}O$, $^{22}Ne/^{20}Ne$) ratios. When the parameters are altered to best reproduce the Ne isotopic data (the impetus for the model), the resonance model results (not shown) show significant deviations from the observations for $^{13}C/^{12}C$ and Ne/O. Deviations, both isotopic and elemental, are also present for heavier ions such as Ca, Fe and Ni.

While the power law function and the combined power law and resonance function yield results of similar quality, there are significant outliers where this simple model does not replicate the observed data, specifically $^{13}C/^{12}C$ for both events and Ar/Si for the

14 November 1998 event. As the inclusion of resonance-related fractionation does not significantly improve the results over those of a simple power law fractionation, resonant enhancements of heavy ions must be a minor effect in these events. Overall, it is clear that the process taking place is more complicated than is modeled here.

The assumption of thermal equilibrium was adopted for the sake of keeping the models simple. In fact, thermal equilibrium for all species is not realistic. It is often observed in the solar wind that charge state distributions for heavy elements such as Fe are not well represented by thermal equilibrium distributions (24,25). Modeling has also shown that different elements freeze-in (stop altering their charge state distributions) at different heights in the corona, corresponding to different source temperatures (26). Additionally, stripping of the ions may be occurring before and/or during acceleration (e.g., 27), altering the initial charge state distribution. Such deviations from thermal equilibrium would result in different enhancement patterns than our models produce. We conclude that more sophisticated models than those presented here are required to understand the abundance patterns in these SEP events.

Remnant Material Theory

Significant amounts of ^{3}He have been detected at energies of ~1 MeV/nucleon during moderately active and quiet time periods, suggesting that there is a substantial volume of the interplanetary medium that contains remnant material from impulsive SEP events (10). It is thought that this material, which is already suprathermal, could be preferentially accelerated by a passing CME-related shock and accelerated to the observed SEP energies. Thus a gradual event (i.e, one in which the particles were accelerated by an interplanetary shock rather than at a flare site) could exhibit some characteristics of an impulsive event, the degree of which would depend on the relative amounts of remnant and coronal (or solar wind) material accelerated by the shock.

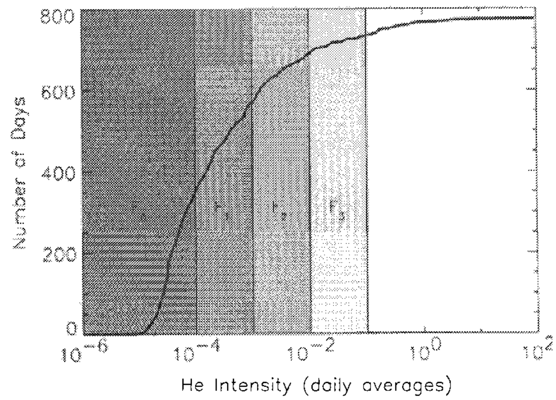

FIGURE 4. Time period selection based on He intensity.

In such a scenario, one would expect other impulsive characteristics to be evident. In addition to being ^{3}He-rich, impulsive events typically have enhanced Fe/O ratios and often have increased $^{22}Ne/^{20}Ne$ ratios (6,28). Periods of low to moderate solar activity have been examined in search of such signatures in the SIS data in an effort to test the remnant material theory. We note, however, that the vast majority of this suprathermal material is expected to be below the energy range of SIS.

Daily averages of the SIS He intensity (I_{He}) at 3.8 – 4.9 MeV/nucleon were sorted by increasing value and the integral number of days with He intensity below a given value was calculated (Figure 4). The data were divided into 4 sets according to different levels of activity: F_0: $I_{He} \leq 10^{-4}$, F_1: $10^{-4} < I_{He} \leq 10^{-3}$, F_2: $10^{-3} < I_{He} \leq 10^{-2}$, and F_3: $10^{-2} < I_{He} \leq 10^{-1}$, where I_{He} is in $(cm^2 \text{ sec sr MeV/nuc})^{-1}$. In addition, days

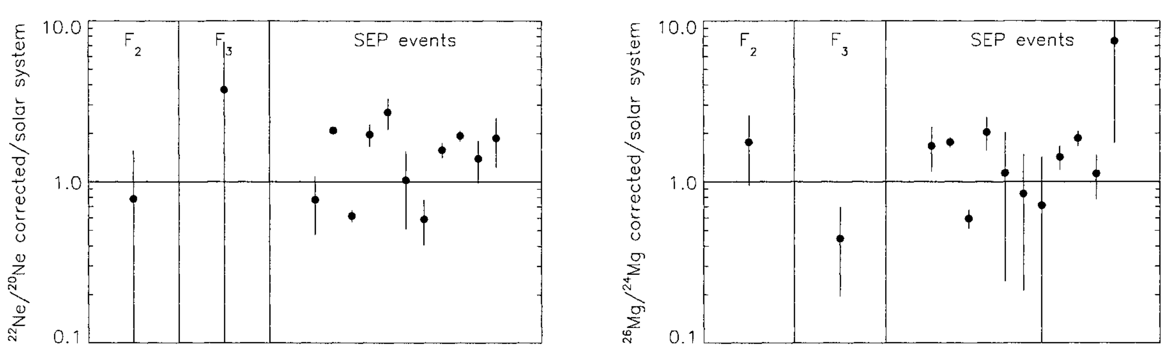

FIGURE 5. Ne and Mg enhancements for different time selections and the 11 SEP events.

containing the tails of the 11 large events were removed from the 4 data sets (the majority of the events themselves were excluded due to the He intensity restrictions).

In order to obtain meaningful Ne and Mg isotope ratios from the different activity levels, the anomalous and galactic cosmic ray (ACR and GCR, respectively) contributions have to be subtracted. From 9/1997 to 11/1999, the ACR component has decreased by a factor of ~20, while the GCR component has been reduced by only a factor of ~2 (29). Additionally the ACR level exhibits factors of ~5 intensity fluctuations on short time scales. Since it has been shown that the ACR and GCR intensity levels scale approximately as powers of the Climax Neutron Monitor data (e.g., 29, 30), we use daily averaged Climax data as a proxy for the overall levels of ACR and GCR contributions. An exponential and a power law energy spectrum are used to represent the ACR and the GCR components respectively. Daily composite spectra are formed from the independently scaled components and summed to produce an overall 'background' spectrum for the days falling within each activity level.

Good agreement is found between the calculated F_0 background and measured Ne spectrum indicating that little solar material is contributing to the F_0 data and that this method of estimating the GCR and ACR background is adequate. The background-corrected Ne and Mg isotopic ratios (as compared to solar system values (14)) are plotted in Figure 5 for the F_2 and F_3 data, and the 11 large SEP events. The F_1 data are consistent with the background spectra and are not shown.

No excess of $^{22}Ne/^{20}Ne$ is apparent in the F_2 or the F_3 data as would be expected if substantial remnant material were present, although the statistical uncertainties are so large that enhancements cannot be ruled out. The uncertainties in the $^{26}Mg/^{24}Mg$ ratios are smaller and the data are also consistent with no enhancement. It should be noted that the energy range of these data is ~20 - ~55 MeV/nucleon and that the solar contribution at these energies is small except in large events. Currently we have not yet resolved the Ne and Mg isotopes at lower energies in the SIS data with sufficient accuracy to present ratios at energies where the solar component is stronger.

Elemental composition measurements in SIS extend down to ~10 MeV/nucleon and a test of the presence of remnant impulsive material is iron, which is typically a factor of ~3 higher in impulsive events (as compared to silicon) than in gradual events. Iron spectra obtained for the 4 activity levels are presented in Figure 6. At high energies, which are dominated by GCRs, all levels exhibit similar intensities. At low energies the solar contribution increases with increasing activity level as expected. Although they are not shown, the silicon spectra show similar trends.

Also shown in Figure 6 is the Fe/Si ratio as a function of energy. An enhancement of ~2 over F_0 levels is apparent at low energies for the F_2 and F_3 data. The sharp decrease in this enhancement near 40 MeV/nucleon is a result of the decrease in the solar contribution to the Fe and Si spectra. From these data we conclude that significant amounts of Fe-enhanced material (possibly from impulsive events) is present during periods of moderate solar activity.

Related to this, a search for ^3He-rich time periods in the SIS data resulted in 92 identified periods greater than 5 hours in length, many of which were not clearly associated with an impulsive SEP event (31). Since the hourly averaged $^3He/^4He$ ratios were required to be consistently greater than 0.10 during these time periods, a lower $^3He/^4He$ enhancement criterion would certainly result in many more time periods, indicating enhancements of ^3He are present during a considerable

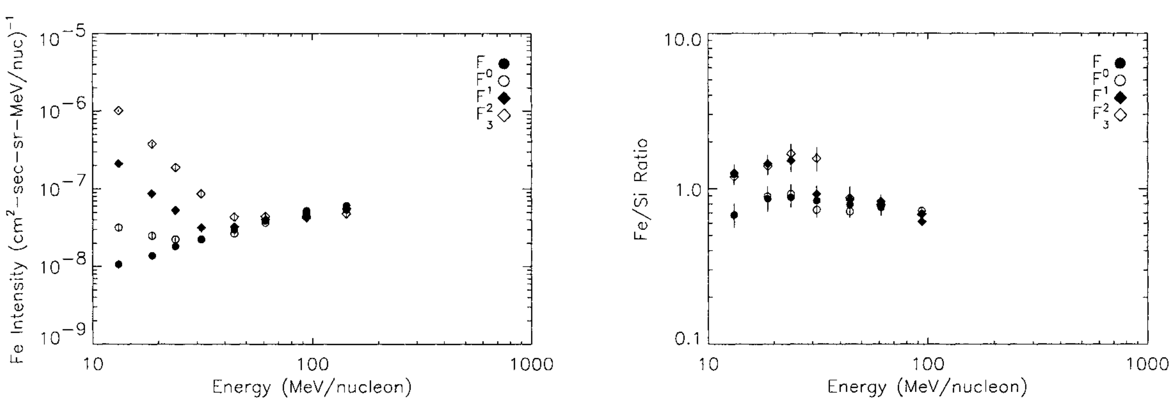

FIGURE 6. Iron intensities and Fe/Si ratios versus energy for different time selections.

portion of the SIS data.

The energy range examined here in searching for evidence of remnant material is much higher than that used by (10), so the vast majority of this suprathermal material is not available for study with the SIS data. However, both the Fe and ^{3}He data suggest that some remnant material might be present even at SIS energies. The absence of any signature in the Ne and Mg isotopic data is not inconsistent with the Fe and He data in that both the energy range and statistical accuracy are much more limited.

While remnant material appears to be present in the interplanetary medium, it is difficult for its presence alone to explain the composition of several of the 11 large events observed by SIS. For example, assuming Fe/O ratios of 1 and 0.134 for impulsive and gradual material respectively (1), to obtain an Fe/O ratio of ~0.8 (typical of these events), a mix of 77% impulsive and 23% gradual material is required. This would result in observed ^{3}He/^{4}He ratios of 8-38% (assuming a ^{3}He/^{4}He ratio of ~10-50% for impulsive and 0.04% for gradual material), inconsistent with the SIS observations of ~0.5% ^{3}He/^{4}He (equivalent to ~1-3% impulsive material).

The high Fe/O (and ^{22}Ne/^{20}Ne) ratio could be a result of Q/M fractionation of the source material which is then subsequently mixed with a small amount residual impulsive material, causing an increase in the ^{3}He/^{4}He ratio but not significantly affecting the heavier ion composition. However, this cannot explain the observed charge states in these Fe-rich events. In addition, Q/M-fractionation effects that favor Fe over O would favor low Fe charge states. However, the average Fe charge state in the 6 November 1997 event is ~15 at ~1 MeV/nucleon (11,32) and ~19 at ≥ 10 MeV/nucleon (32,33), several units higher than the value of ~11 that is typical of 'pure' gradual events (11). Again, this would require essentially all of the material to be impulsive (with an average Fe charge state of ~20 (11)), contrary to the observed ^{3}He abundances.

CONCLUSIONS

The elemental and isotopic data from 11 large SEP events observed by SIS show significant deviations from the composition of the solar system and solar corona. In an effort to understand the fractionation processes that may be occurring we have examined the data in light of three models. While general trends in the data can be reproduced with a Q/M fractionation model, there are particular elemental and isotopic ratios that are not well fit. We find that a simple resonance between the particles and waves at the second harmonic of the ion cyclotron frequency does not adequately represent the observations and when combined with Q/M fractionation does little to improve the fit over that from Q/M fractionation alone.

The idea of remnant impulsive-flare material being swept up by a passing shock may provide an explanation for the observed ^{3}He/^{4}He ratios in many of the large events observed by SIS. However, this theory alone can not consistently explain the high Fe/O enhancements, the high average Fe charge states, and the moderate ^{3}He/^{4}He enhancements found in these events. Combining Q/M-fractionated material with remnant material might explain the elemental and isotopic abundances, but the observed high average charge states would remain a problem.

The improved resolution and statistical accuracy of recent SEP data provide a wealth of information regarding the composition of the source plasma as well as properties of transport and acceleration processes. None of the current fractionation theories adequately account for the data, indicating that there are processes occurring that are not well understood. Clearly Q/M (or a related parameter, such as rigidity) is an important parameter. A complex source or multiple sources (with differing compositions) may also be required (34). In light of these new results the development of a detailed acceleration/transport theory that can be used to model all the observed elemental, isotopic, and ionic charge state fractionations is strongly needed.

ACKNOWLEDGMENTS

This work was supported by NASA at the California Institute of Technology (under grant NAS5-6912), the Jet Propulsion Laboratory, and the Goddard Space Flight Center. Climax neutron monitor data were obtained from the University of Chicago, National Science Foundation grant ATM-9613963.

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