The Solar Cycle Variability of Solar Energetic Particle Composition

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Abstract

Solar particle isotopic composition varies greatly from event to event, apparently due to mass fractionation during particle acceleration and/or transport. We examine whether the amount of this variability changes during the solar cycle and find a strong indication of less isotopic compositional variability at solar maximum than during less active phases. There also seems to be a similiar but weaker association using elemental abundances. The underlying cause of the variability and reasons why it might change over the solar cycle are yet to be determined.

1. Introduction

The Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE) measures the elemental and isotopic composition of solar energetic particles (SEPs) at energies above ~10 MeV/nucleon [4]. Recent studies using SIS have found that SEP isotopic composition varies widely from event to event, with the ^{22}Ne/^{20}Ne ratio varying by more than a factor of 3. The amount of variability, however, seemed to be greater earlier in the mission than at later dates [2]. Here we test whether this change in variability is statistically significant and search for similar variability changes in elemental abundances.

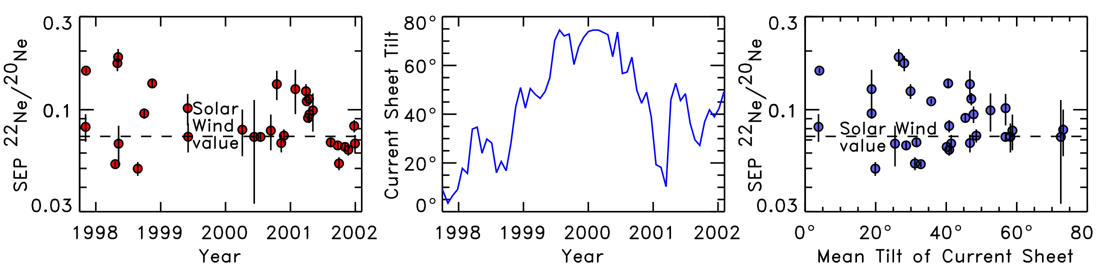

Fig. 1. Event-averaged >15 MeV/nucleon SEP ^{22}Ne/^{20}Ne ratios from ACE/SIS vs time (*left*); mean tilt of the heliospheric current sheet vs time (*center*); ^{22}Ne/^{20}Ne vs current sheet tilt (*right*). *Dashed lines* show the solar wind ^{22}Ne/^{20}Ne value.

2. Analysis

The ^{22}Ne/^{20}Ne ratios in 32 large SEP events are shown in Fig. 1. The observed variability is generally very large compared to statistical or systematic uncertainties, and the amount of variability seems to change. Only 2 of the first 9 events are consistent with the solar wind value, while only 2 of the next 9 events are *in*consistent with it, but the later data do not clearly continue this trend. The variance (of the log of the ratios) was calculated for two time-ordered samples of 16 events each (split at 2000.8). The F-test, which assesses whether 2 samples from general distributions have different variances, indicates that there is a 12.6% chance that the 2 variances are consistent with coming from the same distribution.

It seems reasonable that any real temporal changes in SEP composition or its variability would correlate with the solar cycle. Many parameters can be used to represent the progress of the solar cycle (e.g., sunspot number, F10.7 cm radio flux, etc.) and we have not yet investigated all of them. One such parameter, the mean heliospheric current sheet (HCS) tilt angle calculated by the Wilcox Solar Observatory (http://quake.stanford.edu/~wso/wso.html), is shown in Fig. 1. When plotted vs the HCS tilt angle (*right panel*), the ^{22}Ne/^{20}Ne ratio seems to become less variable and approach the solar wind value as the tilt angle increases. If the HCS-tilt-ordered data are split (at 40.7°) into 2 16-event samples, the F-test shows there is now only a 1.2% chance that the variances of both samples are consistent with the same distribution, strongly suggesting that the variability has in fact changed with the solar cycle (at least for ^{22}Ne/^{20}Ne in these 32 events).

To examine finer-scale changes, the variance was calculated for every 5 consecutive events (Fig. 2). In such a 5-event running variance only every 5th point is independent; to indicate this in Fig. 2 we use 5 different symbol types. In each panel each circle is independent of all other circles, each square is independent of all other squares, etc., but the circles are not independent of the squares since they share events in common in the calculated variance.

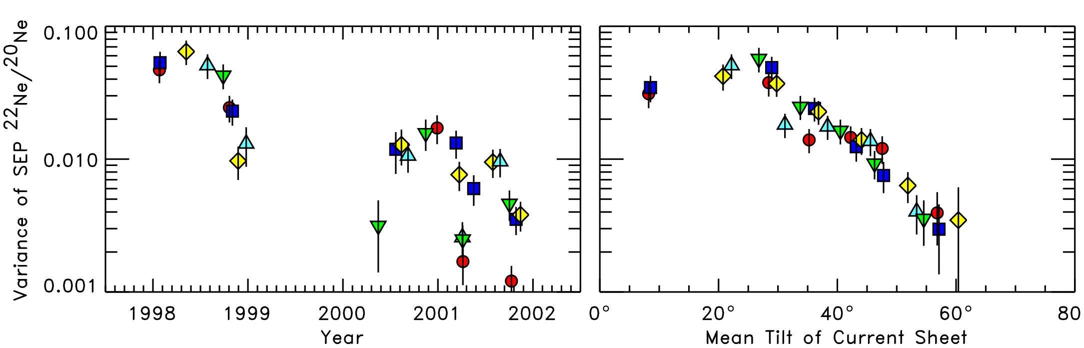

Fig. 2. 5-event running variance of SEP ^{22}Ne/^{20}Ne, ordered by time (*left*) and HCS tilt angle (*right*).

The variance was significantly lower in 2000 and beyond than it was in early 1998. The decrease sets in rather rapidly in late 1998, so combining all data through late 2000 into one set as in the F-test mentioned above diminishes the differences between the two sets. The 5-event running variance when the events are ordered by tilt angle (Fig. 2, *right panel*) shows a very striking, smooth decrease in the variance of the SEP isotopic composition over the solar cycle.

In each SEP event discussed here, SIS has measured elemental abundances of 13 species from C to Ni at 12-60 MeV/nucleon. Event-to-event variability can be much greater for elemental than for isotopic ratios, with Fe/C varying by a factor of >100, for example. Most of the 78 ratios involving the 13 elements also show a tendency towards decreasing variability at increasing tilt angle.

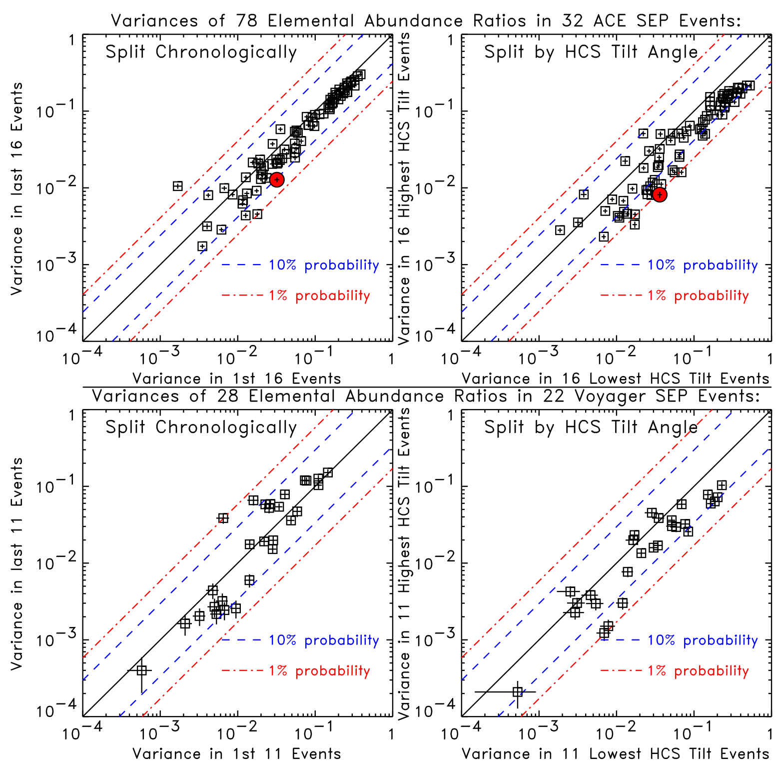

Fig. 3. Elemental abundance ratio variances for 2 equally-sized data samples ordered by time (*left panels*) or HCS tilt angle (*right panels*). *Top panels* use 78 ratios in 32 ACE events; *bottom panels* use 28 ratios in 22 Voyager events.

To summarize the behavior of the 78 elemental ratios, we have again split the 32 events into 2 16-event samples (ordered by time or tilt angle), calculated the variance of each ratio for each sample, and displayed the results in Fig. 3. Each point shows results for a single abundance ratio; ratios between nearby elements (such as C/O) tend to vary less than those between distant elements (such as Fe/C) and fall lower to the left on the plot. For any given point the differences in the variances on the 2 axes are generally small, with the F-test often giving a

>10% chance that the distributions are the same (as indicated by the contours). However, most ratios are somewhat less variable in the later time sample, and this difference between the samples is much greater for the tilt-angle-ordered data. Filled circles show the ^{22}Ne/^{20}Ne points; almost all elemental ratio variances are more equal in the 2 samples than the ^{22}Ne/^{20}Ne variances.

We have also performed the same analysis using 22 SEP events measured by Voyager at 5-45 MeV/nucleon in solar cycle 21 [1]. Only 8 elements were measured, resulting in 28 different ratios, as indicated in the lower panels of Fig. 3. Overall, the variances tend to be somewhat smaller at these lower energies. Splitting the Voyager data in time shows no significant differences between the 2 samples, but once again the sample at higher tilt angles (or higher solar activity) tends to show less variability than the one at lower tilt angles.

3. Conclusions

The variance of the ^{22}Ne/^{20}Ne ratio in 32 large SEP events in solar cycle 23 shows statistically significant changes correlated with the HCS tilt and by proxy with the solar cycle. Changes in elemental abundance variability are generally less than those for ^{22}Ne/^{20}Ne, but $\sim$90% of the ACE/SIS elemental ratios were less variable near solar maximum than during less active times. Also, Voyager elemental data show a similar tendency in solar cycle 21. These findings suggest that fractionation changes during the solar cycle, resulting in more compositional uniformity during the peak of the cycle than during the rising or declining phases.

The cause of this behavior is unknown. Flare material might contaminate gradual events [3] more often near solar maximum when the flare rate is higher. This might cause the composition to become less variable but also less like that of the solar wind, rather than more like it as observed. If SEP mass fractionation is largely a transport effect, differences between magnetically well-connected and poorly-connected events may be larger when the field is well-ordered near solar minimum, while the more disturbed field at solar maximum looks more uniform from event to event. More work is clearly needed to examine correlations with other solar cycle parameters and to verify and explain these observations.

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4. References

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