Proceedings of ICRC 2001: 3132 © Copernicus Gesellschaft 2001

ICRC 2001

Are solar energetic particles an accelerated sample of solar wind?

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Abstract. In the current picture of gradual solar energetic particle (SEP) events, the acceleration is believed to take place at a shock driven by a coronal mass ejection as it moves through the corona and out into the solar wind. It is often assumed that the solar wind provides the seed particles that are accelerated and later observed at 1 AU. We compare solar energetic particle and solar wind composition measurements, focusing on a comparison of the fractionation patterns with respect to first ionization potential. On the basis of several significant differences between the solar wind and SEP compositions, we conclude that most SEPs with energies >5 MeV/nucleon are not simply an accelerated sample of solar wind. Rather, SEPs and fast and slow solar wind appear to be distinct samples of coronal material with significantly different fractionation patterns. This implies that solar energetic particles must be accelerated within a few solar radii of the Sun.

1 Introduction

Solar energetic particle (SEP) events are typically classified into two categories: gradual or impulsive (e.g., Reames 1995). In gradual events particles are accelerated at shocks driven by coronal mass ejections (CMEs) as they pass through the corona and the solar wind. On average, the composition of gradual events is similar to that of the corona. Impulsive SEP events, which are associated with solar flares, are generally less intense, occur more frequently, and are enriched in He, heavy elements (Ne-Fe), and the rare isotope ^{3}He. In this paper we consider only large, gradual events.

It is well known that the elemental composition of energetic nuclei observed in gradual SEP events varies from event to event, apparently reflecting processes that fractionate solar material either before or during SEP acceleration and transport. Fractionation effects generally fall into one of two patterns: (1) Variations that depend on the charge-to-mass (Q/M) ratio of the particles (Breneman and Stone 1985; Reames, 1998) are usually ascribed to acceleration and transport processes. Common examples are Fe-rich and Fe-poor events, characterized by the Fe/O ratio. (2) In addition, SEPs are depleted in elements with first ionization potential (FIP) > 10 eV by a factor of ~4 (see Figure 1). Indeed, it was SEP observations that led to the realization that the solar corona and solar wind are depleted in high-FIP elements when compared to the photosphere (Mewaldt 1980, Cook et al. 1984, Meyer 1985).

This paper compares the FIP-fractionation of SEPs and solar wind observed at 1 AU. As a result of significant differences between the solar wind and SEP compositions, we conclude that most solar energetic particles with >5 MeV/nucleon are not an accelerated sample of the solar wind; rather, SEPs and solar wind appear to be separate, distinct samples of coronal material with significantly different FIP-fractionation patterns.

2 FIP-Fractionation Effects in SEPs and Solar Wind

The two examples of FIP fractionation data in Figure 1 have been averaged over a large number of gradual events. Note that both SEP compilations show a clear FIP fractionation pattern that (if normalized to silicon) has seven elements with FIP >10 eV depleted by a factor of ~3.5 to 4. Helium is the only element that does not fit this pattern – it appears to be depleted by an additional factor of ~2 with respect to the other high-FIP elements.

The depletion of high-FIP elements in the corona is interpreted as evidence for ion-neutral separation processes in which ionized species are transported more efficiently from the photosphere to the corona (e.g., Henoux 1998 and references therein). It is also possible that the relevant atomic parameter in this process is "first ionization time" (FIT) rather than FIP, in which case the fractionation pattern is determined by the time for atoms of a given species to be ionized (see, e.g., Geiss 1998).

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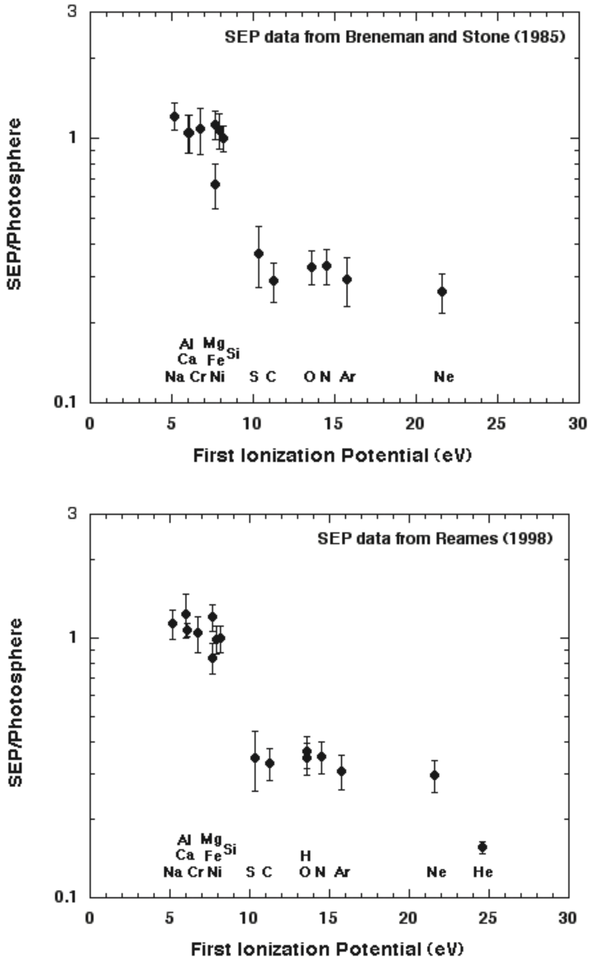

Figure 1: The ratio of average SEP abundances to photospheric abundances (Grevesse and Sauval 1998) is plotted versus FIP for the SEP surveys of (top) Breneman and Stone (1985) and (bottom) Reames (1998). Both plots are normalized to Si. The SEP data show a depletion of elements with FIP > 10 eV by a factor of ~3.5 to 4 (this could also be viewed as an enhancement of elements with FIP < 10 eV). The uncertainties shown include both SEP and photospheric uncertainties.

Garrard and Stone (1994) showed that the degree of FIP fractionation in SEPs varies by up to a factor of ~2 from event to event. We have recently re-examined the evidence for variations in the FIP fractionation of SEPs with additional observations from ISEE-3, SAMPEX, and ACE (Mewaldt et al. 2000; 2001). We confirm the factor of two variation in FIP fractionation from event to event, and further show that the FIP-fractionation process is apparently independent of fractionation effects that depend on Q/M.

The degree of FIP fractionation in the solar wind also varies considerably, with slow solar wind generally showing a greater degree of FIP fractionation than the fast wind. Geiss et al. (1995) showed that the Mg/O ratio in the solar wind is inversely correlated with solar wind speed and with the freeze-in temperature deduced from the O^{+7}/O^{+6} ratio. The similarity of FIP-fractionation effects in SEPs and solar wind suggests that these effects may have a common origin. Mewaldt et al. (2000) suggested two possibilities: 1) the seed population of solar particles could be a variable mix of fast and slow solar wind, or 2) the seed populations of both solar wind and SEPs could be coronal material within which the FIP fractionation varies.

The elemental composition and FIP fractionation in both low and high-speed solar wind streams have recently been studied in detail by von Steiger et al. (2000). They evaluated the degree of FIP fractionation by considering the quantity f, defined to be the abundance ratio [(Mg+Si+S+Fe)/(C+N+O+Ne)] in the solar wind divided by the corresponding abundance ratio in the photosphere. They found f = 2.4 for the slow wind and f = 1.8 for the fast wind (note that sulfur is taken to be a low-FIP element). Evaluating these ratios for SEPs (again with S as low-FIP), we find f = 3.06 using Breneman and Stone (1985) abundances and f = 2.82 using the abundances of Reames (1998). This comparison suggests that FIP fractionation is somewhat less in the slow solar wind than in SEPs, and definitely less in the fast solar wind.

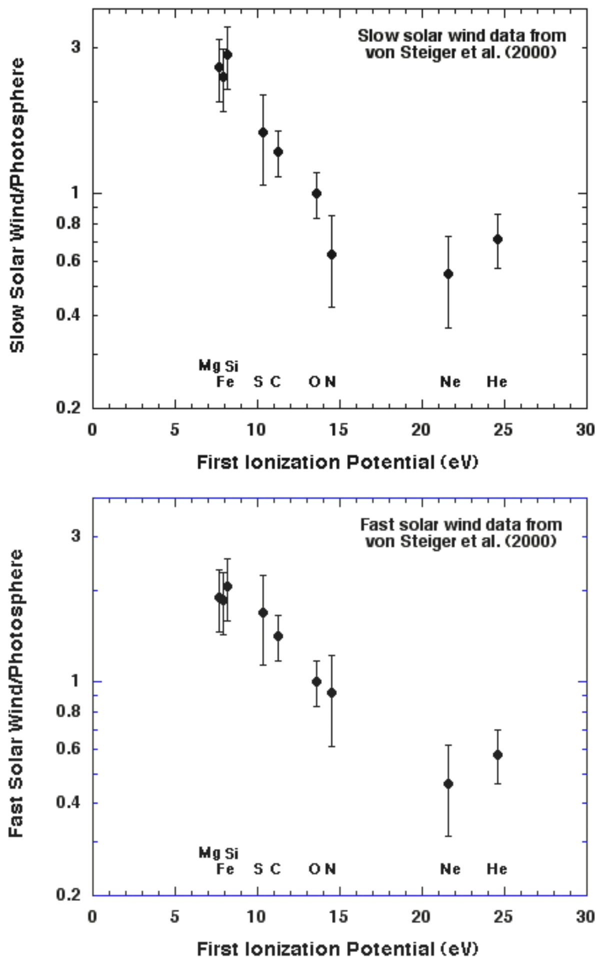

Figure 3: Average abundances in the (top) slow and (bottom) fast solar wind (von Steiger et al. 2000), normalized to photospheric abundances (Grevesse and Sauval 1998), are plotted versus first ionization potential. Uncertainties on the photospheric abundances are added in quadrature with the estimated maximum systematic uncertainties on the solar-wind abundances.

Figure 2 shows plots of the average solar-wind abundances from von Steiger et al. (2001) divided by the photospheric abundances of Grevesse and Sauval (1998). The uncertainties on the data points in Fig. 3 are based on upper limits on the systematic uncertainties, estimated to be <10% for C and O, <30% for N and Ne, and <20% for the remaining elements (von Steiger et al. 2000). Statistical uncertainties in the mean abundances are smaller by a factor of $\sim(1/300)^{1/2}$. While the SEP and solar wind patterns in Figs. 1 and 3 are similar, there are significant differences. In particular, C and S, two elements with FIP values near the 10 eV transition, are more abundant in the solar wind than they are in SEPs. Indeed, von Steiger et al. (2000) consider sulfur to be a low-FIP element, while in SEPs, at least on average, sulfur behaves more like a high-FIP element (Fig. 1). Overall, it does not appear that the solar wind has the same step-like fractionation pattern as that seen in SEPs; the solar-wind fractionation patterns might suggest an exponential dependence on FIP.

4 Discussion

In the standard picture for gradual SEP events, particles are accelerated by a shock driven by a fast CME as it travels through the corona and on into the solar wind. Because CMEs do not originate in coronal holes, where the fast wind originates, one would expect that in most cases the CME-driven shock would be propagating through slow solar wind, at least near the Sun. If most SEPs are accelerated out of the solar wind, they should typically be a sample of slow wind. The comparison of abundance ratios above shows that the FIP fractionation factor for SEPs agrees better with the value for the slow wind than for the fast wind, as noted previously (e.g., von Steiger, Geiss, and Gloeckler 1997).

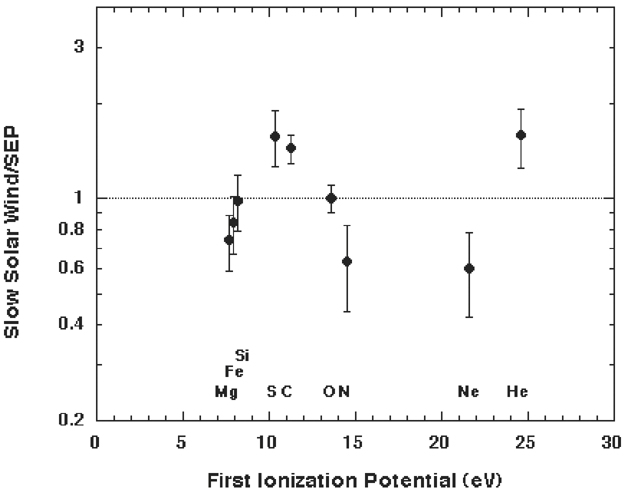

Figure 3: The ratio of slow solar wind to SEP abundances are plotted versus first ionization potential, based on SEP data from Reames (1998) and solar wind data from von Steiger et al. (2001). The SEP uncertainties have been added in quadrature with the estimated maximum systematic uncertainties on the solar wind measurements (von Steiger et al. 2000).

In Fig. 3, which shows the ratio of slow solar wind (SloSW) abundances and SEP abundances, it can be seen that the solar wind and SEP differences are actually quite substantial. In addition to the previously noted differences for He, C, and S, the elements Ne and Mg are also less abundant relative to oxygen. As an example, Fig. 4 shows the C/O ratio measured in 31 SEP events in which the Fe/Si ratio was within a factor of two of the photospheric value (Mewaldt et al. 2000). The typical C/O ratio in SEPs is ~0.45, which agrees with abundance ratios tabulated for the photosphere (Grevesse and Sauval 1998) and solar system (Anders and Grevesse 1989). On the other hand, C/O ≈0.7 in both slow and fast solar wind, with variances that do not overlap the mean SEP value. It does not appear possible to attribute differences in composition such as these to systematic uncertainties in the solar wind abundances, since the systematic error on six of the abundances in Fig. 3 would have to be ~30% to ~60% -- much greater than the maximum systematic errors quoted by von Steiger et al. (2001).

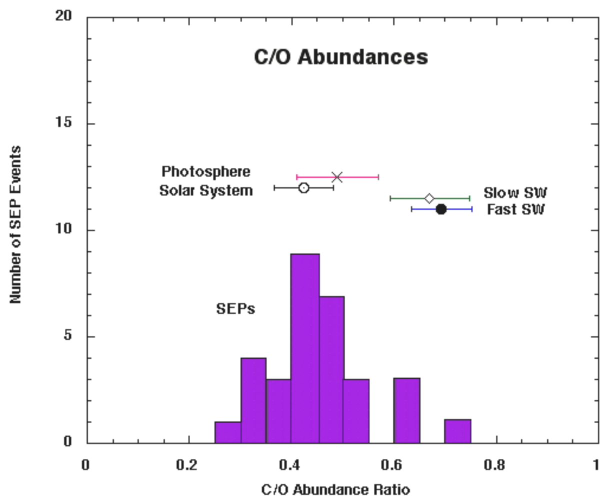

Figure 4: Histogram of the C/O ratio measured in 31 SEP events with 0.45 < Fe/Si < 1.8 (see Mewaldt et al. 2000, 2001). Also shown are the C/O ratios for fast and slow solar wind (von Steiger et al. 2000), and for the photosphere (Grevesse and Sauval 1998) and solar system (Anders and Grevesse 1989).

We are also unable to attribute these differences in any simple way to charge, mass, or Q/M-dependent fractionation effects that might occur during SEP injection, acceleration, or transport. For example in Fig. 5 the SloSW/SEP ratios are plotted versus Q/M, and in Fig. 6 versus nuclear charge (Z). Neither of these (or FIP or FIT) seems to organize the differences. Also, fractionation that occurs during the acceleration of the solar wind cannot explain the SEP and solar-wind differences if SEPs are really an accelerated sample of solar wind. From Figs. 3, 5, and 6 we conclude that the FIP-fractionation patterns observed in the solar wind and SEPs are actually quite different. These differences argue against the hypothesis that most SEPs are simply an accelerated sample of either the slow, fast, or mixed solar wind observed at 1 AU. It is also possible that SEPs originate from a mixture of solar wind with another reservoir of material, but the composition of that reservoir would have to be quite unusual (e.g., a C/O ratio much less than that in SEPs).

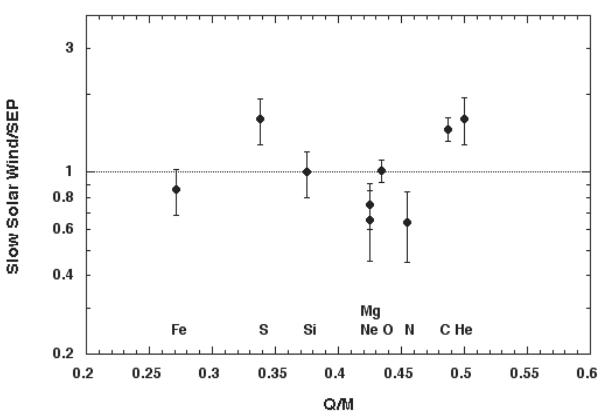

Figure 5: Ratio of slow solar wind to SEP abundances plotted versus the ionic charge to mass (Q/M) ratio measured in SEPs by Leske et al. (1995).

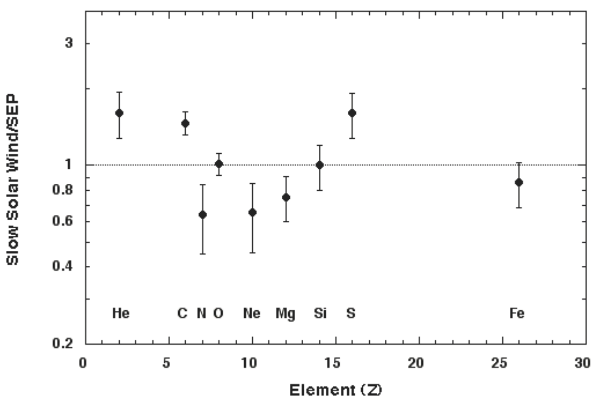

Figure 6: Ratio of slow solar wind to SEP abundances plotted versus nuclear charge (Z). A plot versus mass would be similar.

The FIP fractionation that characterizes the coronal composition is believed to take place in the transport of material from the photosphere to the corona, and as such is a "source" effect rather than an effect of particle acceleration or transport. Indeed, it is known that the degree of FIP fractionation varies within the corona (Feldman 1998). We suggest that solar particles and solar wind are separate samples of coronal material that provide additional evidence for an inhomogeneous coronal composition. If this is the case, it would imply that the majority of SEPs in gradual events with energies greater than ~5 MeV/nucleon originate from coronal material within a few solar radii of the Sun. By comparing SEP onset times with CME images, Kahler (1994) also found that SEP acceleration must take place within a few solar radii (see also Barghouty and Mewaldt 2000).

5 Summary

Both the solar wind and solar particles exhibit a variable degree of FIP fractionation, suggesting that these variations have a common origin. However, the detailed fractionation pattern in long-term averages of these samples of solar material is actually quite different, which suggests that most solar particles with energies >5 MeV/nucleon are accelerated out of a pool of coronal material other than the average solar wind as observed at 1 AU. We suggest that solar particles and solar wind represent separate samples of coronal material that, at least on average, exhibit distinct fractionation patterns that are established before the injection and acceleration of solar particles takes place.

Acknowledgments: This work was supported by NASA at the California Institute of Technology (under grant NAS5-6912), the Jet Propulsion Laboratory, and Goddard Space Flight Center.

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