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Evolution of Suprathermal Seed Particle and Solar Energetic Particle Abundances

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Abstract. We report on a survey of the composition of solar-wind suprathermal tails and solar energetic particles (SEPs) including data from 1998 to 2010, with a focus on 2007 to 2010. The start of solar cycle 24 included several SEP events that were unusually He-poor. We conclude that these He-poor events are more likely related to Q/M-dependent spectral variations than to seed-particle composition changes. We also find that the quiet-time suprathermal Fe/O ratio during the 2008-2009 solar-minimum was dramatically lower (Fe/O ≤ 0.01) than earlier due in part to very low solar activity, but also suggesting contributions from an oxygen-rich source of suprathermal ions of unknown origin.

Keywords: Solar energetic particles, solar wind, pickup ions, solar composition, solar flares
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INTRODUCTION

Among the first solar energetic particle (SEP) events of solar cycle 24 were several He-poor events with He/H from 0.001 to 0.01 (Fig. 1a). At the same time the He/H ratio in the solar wind has decreased by ~50% in the past few years (Fig. 1b), suggesting that the composition of suprathermal ions (~0.05 to ~1 MeV/nuc) may have been evolving as well. This has stimulated an updated study of the quiet-time abundances of key suprathermal ion species.

A variety of data from solar cycle 23 showed that CME-driven shocks accelerate primarily suprathermal ions rather than bulk solar wind (e.g., [1-3]). This is demonstrated by comparing the SEP composition with that of interplanetary suprathermal ions. For example, the frequency of small, ^{3}He-rich SEP events is correlated with the fraction of time suprathermal ^{3}He is present in the interplanetary medium [2,4]. These ^{3}He-rich events are also enriched in Fe and other heavy elements (Fe/O ≈ 1 [1]) and in He (He/H ≈ 0.1 [5]). In addition, CME-shock-accelerated events enriched in ^{3}He are also enriched in Fe and highly-ionized charge states [2]. Finally, the typical low-energy Fe/O ratio in large SEP events (Fe/O ~ 0.3 [3]) is consistent with solar-maximum suprathermal abundances [2], but not with the solar wind composition (Fe/O = 0.120 $\pm$0.024 for slow wind [6] and Fe/O = 0.067 $\pm$0.007 for fast wind [7]).

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Table 1 summarizes suggested sources of suprathermal seed particles near the Sun. Some sources are re-cycled from other solar/interplanetary acceleration processes. A recent addition to this list is energetic neutral atoms (ENAs) from charge-exchange of ions accelerated in the outer heliosphere [11-13]. Voyager data show a relatively stable population of suprathermal ions in the heliosheath originating from accelerated interstellar pickup ions. The resulting ENA population entering the inner heliosphere is a product of heliosheath ion densities and charge-exchange cross sections for making neutrals, with H and O being the most abundant ENAs. Chalov and Fahr [11], and Schwadron and McComas [12] suggest that heliosheath ENAs are an important source of suprathermal pickup ions in the inner heliosphere (see also [13]).

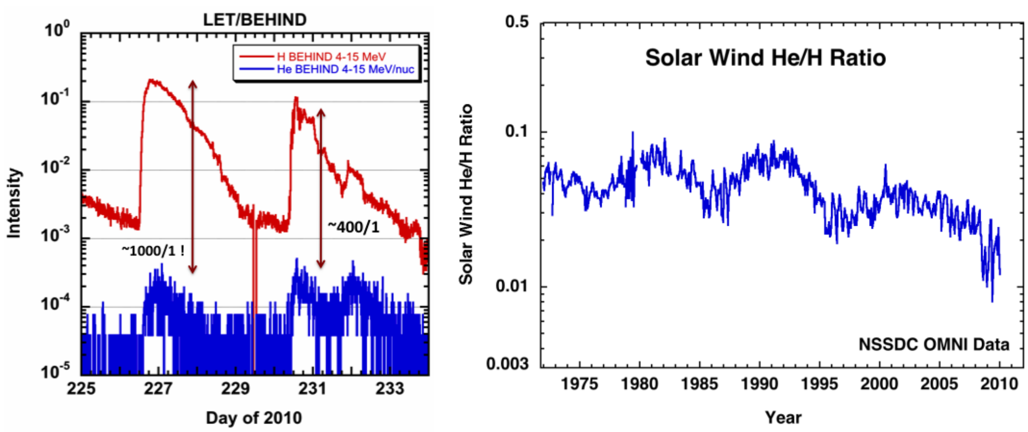

FIGURE 1: (a) Time-intensity profiles for H and He in two SEP events observed by the LET sensor on STEREO-B [8] in August, 2010. Note that the He/H ratio is ~0.001 in the first event and ~0.0025 in the second event. Similar He/H ratios were observed by STEREO-A (separated by 150°). Both SEP events were very He-poor compared to typical He/H ratios of ~0.02 to 0.05 in CME-shock-accelerated SEP events (e.g., [9]). (b) Solar wind He/H ratio based on NSSDC OMNI data (see [10]).

TABLE 1. Sources of Suprathermal Seed Particles

Source	Characteristics	References
Prior impulsive SEP events	Enriched in Fe, He, and ^{3}He	[1,5]
Prior gradual SEP events	Average SEP abundances	[2]
CIR events	C-rich; He and Fe-poor	[14]
Suprathermal solar wind	Slow/Fast solar wind abundances	[6,7]
Interstellar pickup ions	Enriched in He$^+$	[15]
Inner source pickup ions	~ Solar wind composition; once-ionized	[16,17]
Outer source pickup ions	Once-ionized refractory species	[18]
Planetary magnetospheres	~ Solar wind composition	[19]
ENAs from the heliosheath	H and O rich	[11,12,13]
Sun-grazing comets	Enriched C,O with C/O ≤ 0.7	[20,21,22]
CME material	Enriched in He, Mg, Si, Fe	[23,8,24]

OBSERVATIONS

The SEP observations summarized here are from instruments on ACE, SOHO and STEREO. We investigate the frequency of He-poor SEP events using SOHO/EPHIN data [25], which has H and He channels at 4.3 – 7.8 MeV/nuc. At high intensities the outer annular region of each of the two front detectors in EPHIN is automatically disabled. Such periods are potentially affected by background and pile-up effects, and for this reason they have been eliminated. Event averages were based on time periods when EPHIN was in normal operating mode, omitting SEP events if the ~6 MeV/nuc He/H ratio in the high-rate mode differed from that in the normal mode by >50%. This He/H survey is shown in Fig. 2. Events with He/H < 0.01 occur throughout the solar cycle, but the four lowest ratios were in 2007-2010. Note also that ^{3}He-rich events have elevated He/H ratios (see [5]), which, like ^{22}Ne/^{20}Ne and Fe/O, reflect a pattern of over-abundant high-rigidity species in these events [27].

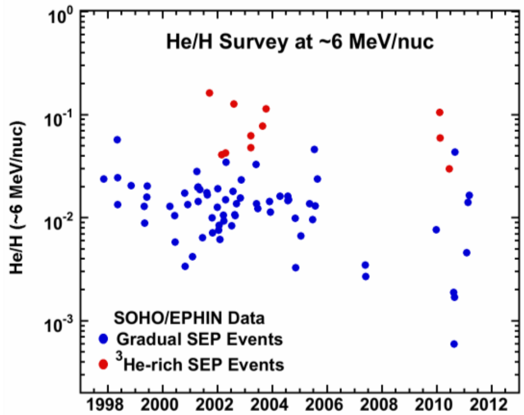

FIGURE 2: He/H ratios measured by SOHO/EPHIN are shown from late 1997 to early 2011 in events identified as "gradual" (associated with CME-driven shocks) and in ten events identified as ^{3}He-rich by ACE/ULEIS [26]. Note that ^{3}He-rich SEP events have higher He/H ratios [5].

An earlier survey of quiet-time suprathermal abundances using ACE/ULEIS data was conducted [28]. Desai et al. [14] and Dayeh et al. [29] also made surveys based on less stringent quiet-time criteria. In this paper we update our 2007 survey [28] by adding data for 2007 – 2010. To avoid composition biases, we let

$$\langle J_i \rangle = J_i[\mathrm{H}]/S_{\mathrm{H}} + J_i[\mathrm{He}]/S_{\mathrm{He}} + J_i[\mathrm{C}]/S_{\mathrm{C}} + J_i[\mathrm{O}]/S_{\mathrm{O}} + J_i[\mathrm{Fe}]/S_{\mathrm{Fe}}, \tag{1}$$

where the J_i are daily 0.16 – 1.28 MeV/nuc intensities of H, He, C, O, and Fe from ULEIS. The five S_x values are constants adjusted so $\sum J_i[x]/S_x = 1$ for each x when summed over all 2007-2010. We then selected intervals of ≥3 consecutive days with $\langle J_i \rangle \leq 8\mathrm{x}10^{-5}$, $8\mathrm{x}10^{-5}$, $4\mathrm{x}10^{-5}$, and $2\mathrm{x}10^{-4}$ cm^{-2}sr^{-1}s^{-1}MeV/nuc^{-1} for years 2007-2010, respectively. Similar criteria were used in the 1998-2007 study. In Fig. 3 we show the resulting abundance ratios for 1998-1999 through 2010. The suprathermal abundances clearly undergo significant solar-cycle variations, as discussed below. Also shown are average abundance ratios for the corona, slow solar wind, CIR events, and 5 – 12 MeV/nuc SEP events.

DISCUSSION

We first discuss time variations of the element abundance ratios in Fig. 3. The He/H ratio varies by a factor of ~2 from solar minimum to solar maximum. It is lower in 2010 than during the preceding solar maximum, perhaps by an amount comparable to the decrease in the solar wind He/H ratio at this time (see Fig. 1). The He/H and He/O ratios may be influenced by interstellar He^+, which is preferentially accelerated in CIRs [30], such that $He^+/He \approx 0.25$ in 1-AU CIR events [31]. CIR ions can diffuse in near the Sun and be SEP seed particles. While a lower solar wind He/H ratio could contribute to the lower He/H ratios in 2007 – 2010, it could not account for SEP events that are He-poor by a factor of ~10 without very large He/H fluctuations.

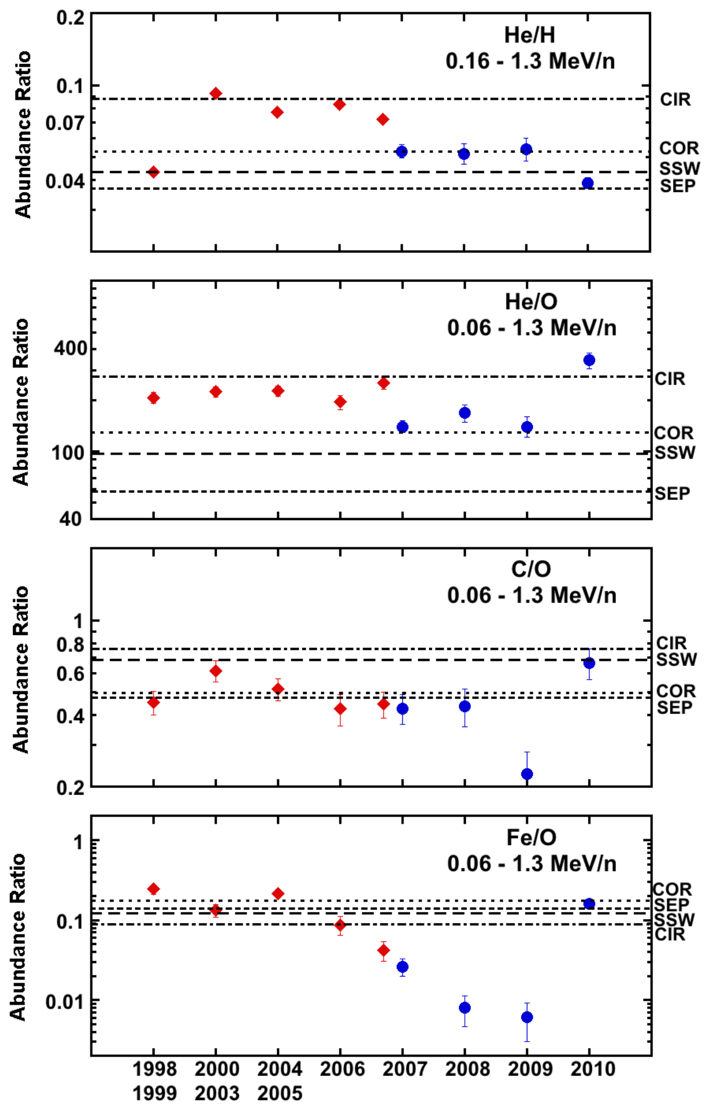

FIGURE 3: Plot of four abundance ratios for quiet-time periods from 1998-1999 (combined) to 2010. The red points are based on similar quiet-time criteria to 2007-2010 (see text). Also indicated are average abundance ratios for coronal [32], slow solar wind [6], gradual SEP [9], and CIR material [33,9].

Surprisingly, He/H and He/O are similar to CIR levels at solar maximum. Our 2000-2003 C/O ratio is midway between CIR and SEP values (similar to Desai et al. [14]). There may be excess He from impulsive SEP events (Fig. 2), and our strict quiet-time criteria may eliminate gradual SEP contributions. Mason et al. [33] report 19 CIRs in 2000-2005. Remnant CIR ions may dominate very quiet non-SEP periods.

The 2008-2009 solar-minimum Fe/O ratio was >30 times lower than in 1998-1999; reflecting in part the near absence of impulsive ^{3}He-rich events [34]. A reduced ^{3}He-rich event rate should also decrease suprathermal He/H, but He/H only decreased by a factor of ~2, suggesting that other He sources dominate. The 2010 Fe/O ratio quickly returned to a level near that of last solar maximum, undoubtedly due to an increased ^{3}He-rich event rate [4]. The fact that Fe/O in 2008-2009 was >8 times lower than SW/SEP/coronal values suggests an oxygen-rich contribution. Candidates to be investigated include ACR oxygen, heliosheath ENAs, and remnant O from upstream magnetospheric events. Observed energy spectra rule out ACR oxygen. Also, while O^{+1} has been observed in CIR events [31], it has not been reported in SEPs. The C/O ratio was similarly low in 2009 compared to 1998-1999. If the hypothesized oxygen-rich contribution was twice as great in 2007-2009 (due to reductions in other sources) it might explain lower He/O and non-CIR-like C/O in 2007-2009. Thus, He/O and C/O constrain how much of the Fe/O drop could be due to oxygen-rich ENAs.

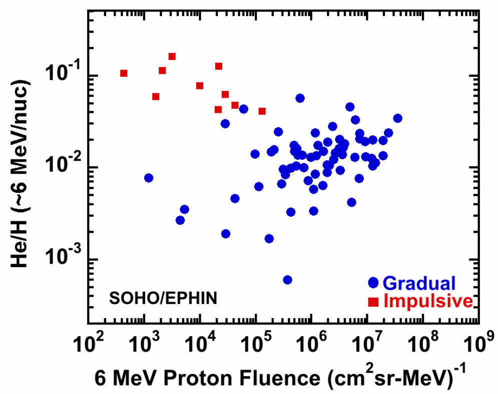

FIGURE 4: The He/H ratio from 4.3-7.8 MeV/nuc measured by SOHO/EPHIN is plotted versus the 6 MeV proton fluence. Included are 70 gradual SEP events identified by ACE/SIS from 1997 – 2010 and ten impulsive SEP events identified by ACE/ULEIS (e.g., [36]).

Although the 2007-2009 yearly-average suprathermal abundances do not seem to easily account for events with He/H < 0.01, there is another possibility. Typical energy spectra in gradual SEP events have a double power-law shape, with spectral breaks that depend on the charge-to-mass (Q/M) ratio such that He spectra break at a lower energy/nuc (e.g., [35]). In the largest events He spectra break at energies ranging from ~10 to ~25 MeV/nuc. However the first cycle-24 events were less intense than most cycle-23 events. If the He spectra break well below ~6 MeV/nuc this may lead to He-poor events. As a test, Fig. 4 shows the He/H ratio versus the proton fluence at 6 MeV. Note that the He-poor events are relatively small, and there appears to be a correlation between He/H and the proton fluence in gradual events (correlation coefficient R = 0.23), supporting this hypothesis. In addition, energy spectra from ACE and SOHO for the first event in Fig. 1a give a H/He ratio that varies from ~1000 at 6 MeV/nuc to ~60 at 0.2 MeV/nuc, confirming a spectral break below 1 MeV/nuc.

In summary, the low SEP He/H ratios in 2007-2010 are more likely due to Q/M-dependent spectral effects than to large changes in suprathermal He/H. Investigating additional SEP H and He spectra can confirm this. The most surprising result in this survey is the quiet-time suprathermal Fe/O ratio of 0.0071 (+0.0031, -0.0023) in 2008-

2009, ~8-25 times lower than known solar/interplanetary suprathermal ion sources. In addition, 2007-2009 data provide limited support for an oxygen-rich source of unknown origin (possibly also H-rich). These and other possibilities will be investigated by comparing year-to-year absolute intensities with possible source variations, by relaxing quiet-time selection criteria, and by looking on finer time scales.

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