Observations of systematic temporal evolution in elemental composition during gradual solar energetic particle events

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Abstract. The *WIND*/EPACT experiment offers a ~100 fold increase in collecting power over instruments flown in previous solar cycles, thus allowing unprecedented detailed studies of temporal evolution in gradual solar energetic particle (SEP) events. We present hourly *WIND*/EPACT observations at ~2-10 MeV/nuc from the 20 April 1998 and 26 August 1998 SEP events. These observations show striking patterns in elemental composition which evolve in a systematic fashion throughout the events' several-day durations. These data, combined with theoretical modeling in a companion *Letter* [*Ng et al*. 1999], suggest that a dynamic Alfvén wave field, generated primarily by streaming energetic protons, is responsible for the complex behavior which is observed.

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Introduction

Elemental composition is a powerful probe of the acceleration and transport of solar energetic particles (SEPs). Solar ions heavier than He are partially ionized to varying degrees and thus have a range of mass-to-charge (A/Q) ratios [*Luhn et al*. 1984; *Möbius et al.* 1999 and references therein]. Comparing elemental abundances makes it possible to disentangle energy- and rigidity-dependent effects. For so-called "gradual" particle events, in which shocks driven by fast coronal mass ejections (CMEs) produce high particle intensities [*Kahler* 1992; *Gosling* 1993; *Cliver* 1996; *Reames* 1997], the generation of Alfvén waves by streaming energetic particles (primarily protons) is of particular importance [*Lee* 1983; 1997]. These waves not only play a key role in acceleration (by scattering particles back and forth across the shock) but also govern subsequent transport away from the shock and through interplanetary space.

In general, instrumental collecting power has limited previous studies [e.g. *Mason et al.* 1984; *Cane et al.* 1991; *Reames* 1990; 1995] to event-integrated quantities. These integrations hide many aspects of the inherently dynamic and time-dependent wave-particle interactions. In this *Letter*, we report new high-precision measurements of the temporal evolution of SEP composition from the Energetic Particles, Acceleration, Composition and Transport (EPACT) experiment [*von Rosenvinge et al.* 1995; *Reames et al*. 1997] aboard the *WIND* spacecraft. Measurements come mostly from the Low Energy Matrix Telescope (LEMT) in EPACT, which has a collecting power of 51 cm^2-sr and provides nearly 4π-sr coverage. In order to elucidate the fundamental physics of SEP production, we focus on "clean" events, in which interpretation is not obscured by multiple injections or complex interplanetary conditions. A companion *Letter* [*Ng et al. 1999*] presents theoretical modeling of these observations.

20 April 1998 Solar Particle Event

In terms of total proton fluence above 10 MeV, the 20 April 1998 solar particle event is the largest event seen thus far in Solar Cycle 23. The Solar and Heliospheric Observatory (*SoHO*) first detected a large CME near the western limb at ~3 R_{SUN} at 10:07 UT. This CME was very fast, with a projected speed near the nose of ~1600 km/s [*C. St. Cyr, private communication*]. An M1.4 x-ray flare began at 09:38 UT and lasted 100 minutes, with peak intensity at 10:21 UT [*Solar Geophys. Data (SGD)* 1998a]. No Hα flare has been reported in association with this event, but the peak x-ray intensity observed on *Yohkoh* during this period was at S23W87 [*J. Mariska, private communication*].

At the time of this event, *WIND* was located ~220 R_E sunward of Earth and nearly on the Sun-Earth line. Figure 1 shows hourly-averaged intensities from *WIND*/EPACT. The highest intensities in the ~2 MeV proton channel are near the streaming-limit of several hundred protons/cm^2-s-sr-MeV identified by *Ng and Reames* [1994].

The far-eastern flank of the CME-driven shock arrived at *WIND* on 23 April 1998 at 17:30 UT. This arrival time corresponds to a mean transit speed from the Sun of ~520 km/s, much smaller than the initial ~1600 km/s observed by *SoHO* for the nose of the CME. Upon arrival at *WIND*, the shock was too slow to be an efficient particle accelerator, and no increases were observed in EPACT particle intensities.

Interpretation of the 20 April 1998 event is not complicated by the presence of other events. For roughly a week before the event, interplanetary particle intensities were near solar-quiet levels, so that the CME-driven shock expanded through field lines which were not already populated with particles and waves from a preceding event. Furthermore, no additional injection of energetic particles can be identified during the event. *SoHO* reported an eastern-limb CME at ~1400 km/s at ~06:00 UT on 23 April. However, particle intensities from far-eastern events are often small and generally exhibit long rise times (on order of ~1-2 days) at Earth [*Reames et al.* 1996]. If this second CME did eventually produce energetic particles at *WIND*, they were at levels well below the late-stage intensity of the 20 April event itself.

Elemental Composition Variations

Figure 2 shows hourly-averaged elemental composition ratios in three energy bins from *WIND*/EPACT. All ratios have been normalized to reference coronal values given by *Reames* [1995]. These reference values were derived by summing heavy-ion fluences at 5-12 MeV/nuc in 43 gradual events observed in Solar Cycles 21 and 22. For example, a relative-to-corona Fe/O ratio of 4 in Figure 2 corresponds to an actual Fe/O ratio of 4 x 0.134 ~ 0.54.

The variations in Figure 2 are clearly systematic and well-organized; they are not random fluctuations, dominated by changes in the magnetic flux tube. The evolution of Fe/O is particularly striking. In the first few hours of the event, Fe/O drops rapidly from an enhanced value. Given the flare location (~W87) and solar wind speed, it is unlikely that this initial Fe enhancement originates from a flare. The Fe/O ratio then rebounds and rises over the next ~12 hours, until the time of the event's peak intensity. Fe/O declines exponentially over the next two days, until shock passage, at which point Fe/O flattens out. The behavior of Fe/O is mirrored by He/O, which declines (increases) while Fe/O rises (falls).

The He/H ratio at ~2 MeV/nuc in the left panel of Figure 2 is especially noteworthy. For most of the event, the temporal evolution in this ratio is opposite to that of Fe/O. Because of the Fe charge state (see below), the numerator has ~twice the rigidity of the denominator in both of these ratios. Different temporal behavior in these two ratios would not be expected if only scattering from a background Kolmogorov wave-spectrum were involved. The difference between Fe/O and He/H in this figure suggests that a dynamic wave spectrum, generated by the streaming energetic particles themselves, plays a fundamental role in this event. (See *Ng et al.* [1999].)

The middle panel of Figure 2 shows composition ratios at 3.2-5.0 MeV/nuc, including additional elements. These data are well-organized by A/Q values[1], with (1) the largest enhancements in Fe/O, (2) a suppression in He/O, and (3) other elements, with intermediate A/Q values, falling in between.

[1] The A/Q ordering in the middle panel of Figure 2 is consistent with *ACE* charge-state [*Möbius et al*. 1999] and isotope [*R. Leske et al., in preparation*] measurements for this event. For example, *ACE* gives $\langle A \rangle / \langle Q \rangle = 2.48 \pm 0.01$ and 2.52 ± 0.04 for O and Ne, respectively. Ne and O thus have equal A/Q values, and the Ne/O ratio in Figure 2 shows little variation during the event.

Evolution at 5-10 MeV/nuc (right panel, Figure 2) is similar in shape to lower energies, but with overall normalizations pushed downward. At the peak of the event, the 5-10 MeV/nuc Fe/O is near its coronal value but later becomes strongly suppressed. At higher energies from the Advanced Composition Explorer (*ACE)*, Fe/O shows even larger depletion [*T.T. von Rosenvinge, private communication*]. The clear A/Q ordering of the middle panel apparently breaks down at 5-10 MeV/nuc, with Si/O (and even He/O and C/O late in the event) above Fe/O. These re-ordering effects are too large to be explained by time- or energy-dependence in charge states.

Particle Spectra vs. Rigidity

Composition ratios in Figure 2 compare intensities in common velocity (*i.e*., MeV/nuc) bins. The origin of the variations is best understood, however, by examining particle spectra as functions of *rigidity*. To derive such spectra, we assume typical gradual-event charges states (Q=1 for H, Q=2 for He, Q~7 for O, and Q~14 for Fe [*Luhn et al*. 1984]). Using lower charge states reported for this particular event (Q~6.5 for O and Q~11 for Fe [*Möbius et al*. 1999]) does not change the qualitative interpretation of our results. We further assume that charge states are independent of energy in this event, as suggested by *ACE* results [*Möbius et al.* 1999].

The particle spectra in Figure 3 show a pronounced flattening at low rigidities, which correspond to proton energies of ~1-10 MeV. At higher rigidities, the spectra steepen into power laws. Since simple shock theory predicts power laws near the shock, this flattening suggests that escape from the shock region into interplanetary space has been preferentially impeded at low rigidities. Alfvén waves generated by streaming energetic protons provide a natural mechanism for throttling escape from the shock region [*Ng & Reames* 1994].

Rigidity-dependent escape which flattens these spectra also distorts abundance ratios evaluated at common MeV/nuc but different rigidity. Iron (because of its higher A/Q) escapes the shock region more easily than oxygen, which in turn escapes more easily than helium, *etc*. Thus, Fe/O enhancements in Figure 2 are more properly seen as suppressions of oxygen.

Moreover, the relevant wave field (and hence rigidity-dependent filtering) generally evolves during the event: the shock's decreasing ability to accelerate particles causes wave generation to decline, and expansion and co-rotation change the observer's connection point to the shock front. These dynamics may account for overall temporal evolution in abundance ratios, without invoking changes in ionic charge states or source plasma composition. (See *Ng et al*. [1999].)

As an additional check, Figure 4 shows ratios calculated at equal *rigidities*, rather than equal energies. These ratios are not particularly useful for determining coronal composition, nor does rigidity alone order all aspects of the data. However, apart from the rise phase of the event, these ratios show little evolution. The relatively small variations that remain in Figure 4 may reflect other factors, such as flux-tube variations.

Finally, we note that the clarity with which the 20 April 1998 event reveals the underlying wave-particle physics is unusual but not unique. Fe/O shows similar evolution in the 23 September 1978 particle event [*Reames* 1990; *von Rosenvinge & Reames* 1979], albeit with large statistical errors due to instrumental collecting power of only ~0.5 cm^2-sr. Spectra also show the same flattening as seen in Figure 3.

26 August 1998 Energetic Storm Particle Event

Whereas the 20 April 1998 event gave the opportunity to observe particles which escaped from a distant shock-accelerator, the so-called "energetic storm particle" (ESP) event of 26 August 1998 offered *in-situ* observations near a powerful shock. Intensities of ~MeV particles in this event were the highest observed so far at Earth in Solar Cycle 23 and coincided with arrival of a strong interplanetary shock ~34 hours after an X1.0 flare at N35E09 [*SGD*, 1998b]. This shock was presumably driven by a fast halo CME. (*SoHO* observations were unavailable for this event.)

The 20 April 1998 event shows composition variations due to preferential escape of high A/Q species from the shock region. One might therefore expect to see depletions of high A/Q species near a shock. As shown in Figure 5, this is indeed the case. As the shock approaches, Fe/O drops more or less smoothly. As the shock moves beyond 1 AU, Fe/O recovers somewhat but generally remains suppressed in the post-shock region. Si/O and He/H show similar behavior.

Figure 6 shows spectra vs. rigidity shortly before shock arrival. These spectra are not pure power laws. However, as expected, they do *not* exhibit the dramatic flattening seen at low rigidities in the 20 April 1998 and 23 Sept. 1978 events.

Discussion and Summary

Elemental composition in large, gradual solar particle events evolves in a complex but clearly systematic fashion. This evolution is not dominated by random fluctuations. These detailed *WIND*/EPACT observations -- including the striking time histories, the complex A/Q ordering of the composition ratios, the rigidity spectra, and comparisons between distant and nearby shocks -- offer significant challenges for theoretical modeling. In fact, these challenges may be insurmountable for static transport models which neglect coupling between time-dependent waves and particles.

Qualitative considerations in this *Letter* suggest that Alfvén waves amplified by streaming particles [*Lee* 1983; 1997; *Ng & Reames* 1994] may hold the key to understanding these data. In fact, as demonstrated by *Ng et al*. [1999] in the following *Letter*, modeling which explicitly accounts for the central role and dynamic nature of these waves shows great promise. Preliminary studies of other events, including those with very different morphologies in the composition evolution, indicate that particle-generated waves may generally account for many significant features of large SEP events.

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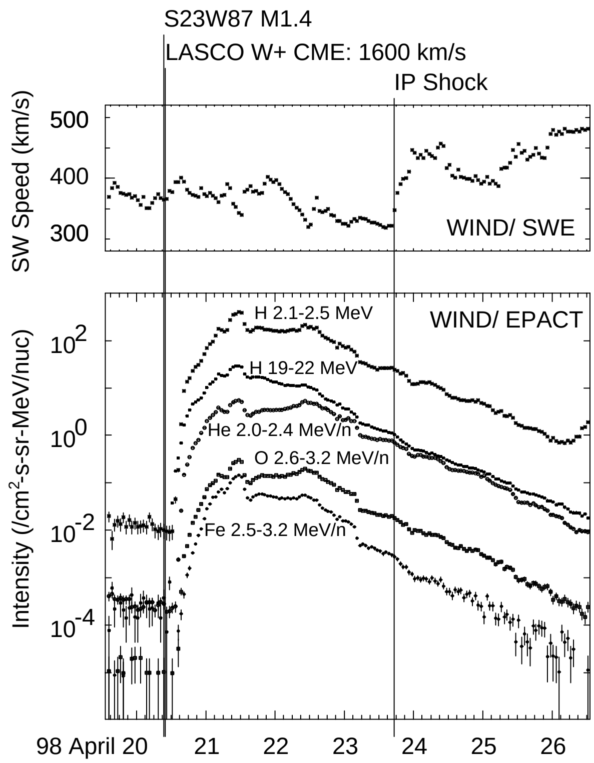

Figure 1. *WIND* hourly-averaged solar wind speed (top) and energetic particle intensities (bottom) during the 20 April 1998 solar particle event.

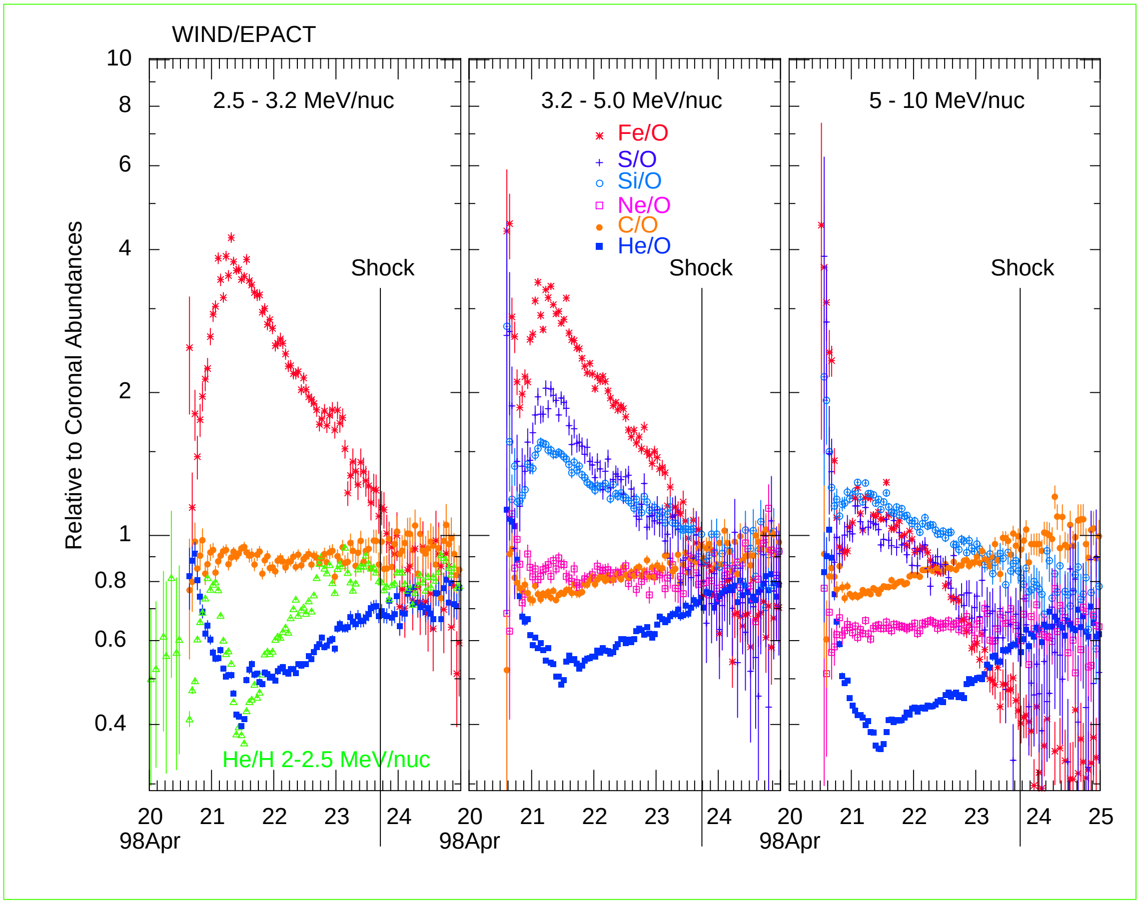

Figure 2. Hourly-averaged elemental composition ratios (normalized to coronal values [*Reames* 1995]) in three energy intervals from *WIND*/EPACT during the 20 April 1998 solar energetic particle event.

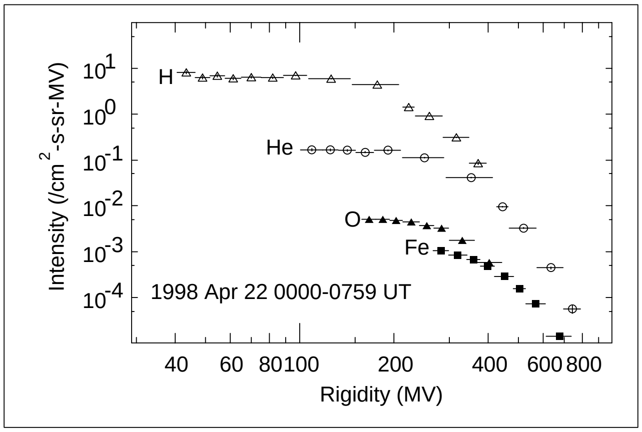

Figure 3. Particle intensities *vs*. rigidity on 22 April 1998 at 0-8 UT. H and He spectra are from NASA/GSFC instruments on *IMP8*; O and Fe from *WIND*/EPACT.

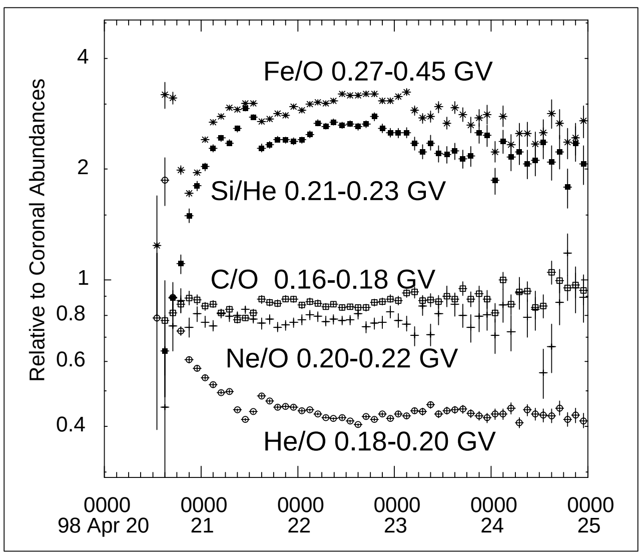

Figure 4. Elemental composition ratios (normalized to *Reames* [1995]) calculated in rigidity intervals. Rigidities were evaluated from observed energies assuming nominal gradual-event charge states [*Luhn et al.* 1984].

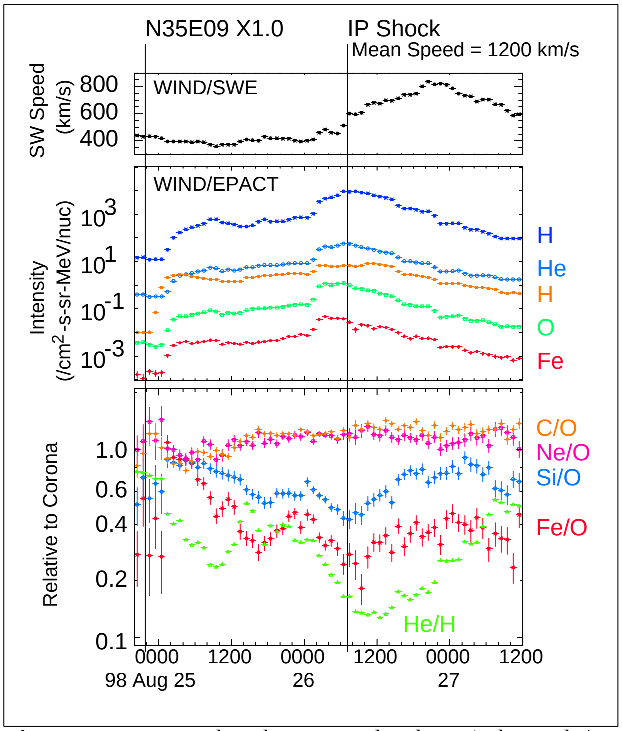

Figure 5. *WIND* hourly-averaged solar wind-speed (top), particle intensities (middle, same energies as in Fig. 1), and elemental ratios (bottom) during the 26 August 1998 event. Ratios are at 3.2-5 MeV/nuc except He/H, which is at 2-2.5 MeV/nuc.

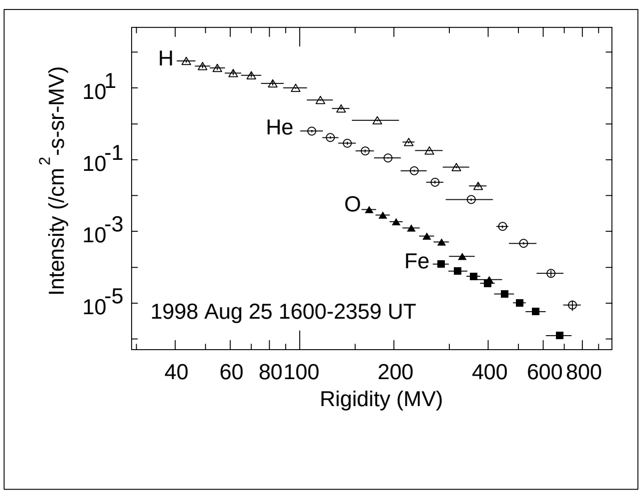

Figure 6. Particle intensities *vs.* rigidity (as in Fig. 3) shortly before shock arrival in the 26 August 1998 ESP event.