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ENERGETIC PARTICLE ABUNDANCES AS PROBES OF AN INTERPLANETARY SHOCK WAVE

D. V. Reames
NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD 20771; reames@milkyway.gsfc.nasa.gov
and
A. J. Tylka
E. O. Hulburt Center for Space Research, Code 7652, Naval Research Laboratory, Washington, DC 20375; allan.tylka@nrl.navy.mil
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ABSTRACT

We examine the unique abundance variations of Fe/O and He/H in solar energetic particles from a W09 event of 2001 April 10 that have leaked through the flank of an interplanetary shock launched from W04 on April 9. Shock waves from both events reached the *Wind* spacecraft on April 11. During the second event, both Fe/O and He/H began at low values and rose to maxima near the time of passage of the shock waves, indicating greater scattering for the species with the highest rigidity at a given velocity. Strong modulation of Fe/O suggests preferential scattering and trapping of Fe by the wave spectrum near and behind the intermediate shock. A significant factor may be the residual proton-generated waves from the very hard proton spectrum accelerated by the early shock wave prior to the onset of the second event. Thus, ion abundances from the later event probe the residual wave spectrum at the earlier shock.

Subject headings: acceleration of particles — shock waves — Sun: abundances — Sun: coronal mass ejections (CMEs) — Sun: particle emission

1. INTRODUCTION

Recent evidence has shown that solar energetic particles (SEPs) in the large "gradual" SEP events are accelerated at shock waves driven out from the Sun by coronal mass ejections (CMEs; Kahler et al. 1984; Gosling 1993; Reames 1995, 1999, 2001; Kahler 1994, 2001; Tylka 2001). The acceleration is mediated by proton-amplified Alfvén waves produced as the particles stream away from the shocks (Bell 1978; Lee 1983, 1997). In large SEP events, wave growth also provides an upper bound to observed proton intensities at the "streaming limit" when high wave intensities cause enough particle scattering to throttle the streaming and, hence, the growth rate of the waves (Ng & Reames 1994; Reames & Ng 1998). In the streaming limit, increases in particle and wave intensities near the shock steepen the local spatial gradients with little affect on proton intensities out at 1 AU.

Even at a fixed velocity, ions with different charge-to-mass ratios, *Q*/*A*, resonate with different regions of the wave spectrum, causing complex temporal variations in their abundances (e.g., Tylka, Reames, & Ng 1999). Different particle species resonate with proton-generated Alfvén waves with a wavevector $k = B/\mu P$, where P is the particle's magnetic rigidity and μ is the cosine of its pitch angle with respect to the magnetic field, B. Ng, Reames, & Tylka (1999) modeled the evolution of the particles and waves in space and time as they propagate from the shock to the observer, successfully reproducing the qualitative behavior that was observed (see also Tylka 2001).

Near the shock, particles are accelerated as they are scattered back and forth across the shock by proton-generated waves. The spectra of ions and waves can approach an equilibrium for which all ions have power-law spectra with a spectral index that depends only on the shock compression ratio (Lee 1983). In this case, the wave spectrum at the shock is always flatter than k^{-2}, which is obtained at the maximum shock compression ratio of 4; for this spectrum, the scattering mean free path is independent of rigidity. It is generally assumed that the element abundances accelerated by the shock are identical to those of the injected "seed population"; it is further assumed that these abundances do not vary with energy/nucleon or with time. However, as the protons stream away from the shock, differences in their velocity and transport can cause their spectrum to flatten and even roll over at low energies. These altered proton spectra generate complex wave spectra, depending on position and time, through which the heavier ions must pass. Thus, particle abundances probe either the ambient or self-generated wave spectra away from the shock.

In SEP events that are magnetically well connected to the observer, the initial rapid rise of intensities magnifies differences in the net scattering of different ion species. Species with more scattering will be delayed, by even small changes in their mean pitch angle, and lag other species as their intensities rise. This effect is amplified by comparing the behavior of abundance ratios, such as Fe/O or He/H, at the same velocity. Such ratios will begin at high values and then decline initially when the species in the denominator is scattered more, and conversely. Let us suppose that all particles are transported through an initial Kolmogorov wave spectrum where the scattering mean free path $\lambda \sim P^{1/3}$. In this case, Fe will be scattered less than O, Fe will arrive earlier, and Fe/O will begin at high values and decrease to a constant value as a function of time. He/H will behave similarly.

Reames, Ng, & Tylka (2000) compared the initial abundance behavior in small and large SEP events. In small events, or in events with soft proton spectra (Ng, Reames, & Tylka 2001; Reames 2001), both Fe/O and He/H declined with time as described for an ambient Kolmogorov wave spectrum. For intense events, however, Fe/O declined initially while He/H rose. This was understood in terms of wave amplification in the large events as follows. If we assume initially that $\mu \sim 1$, then 2 MeV H will resonate with waves generated by 2 MeV protons, but He at 2 MeV amu^{-1} will resonant with waves amplified by protons of twice its velocity, ~8 MeV protons. The 8 MeV protons arrive about an hour earlier, and given a sufficiently high intensity and flat spectrum, they will produce waves that preferentially scatter and delay the He, causing He/H to rise from an initially depressed value (see Reames et al. 2000 and Ng et al. 2001).

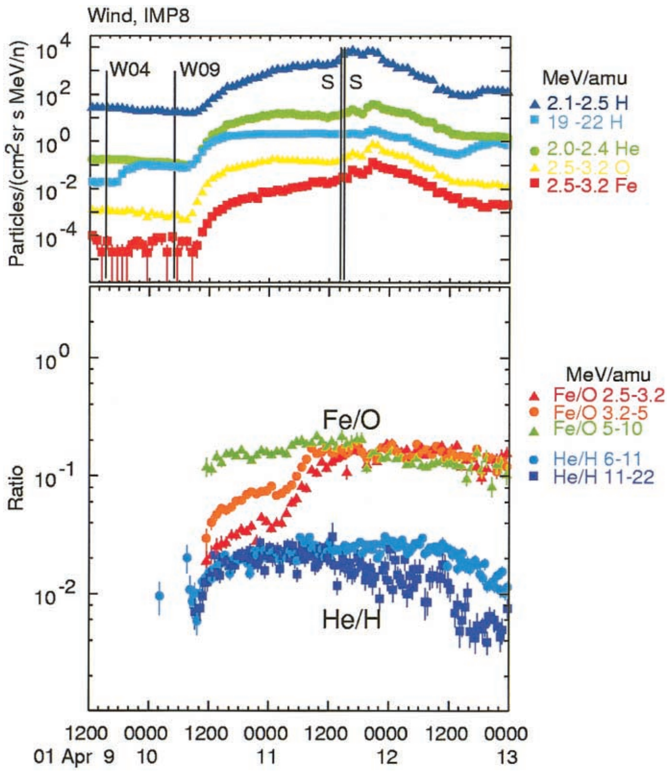

FIG. 1.—Particle intensities and abundance ratios vs. time during the 2001 April 9–13 period. A particle increase for event 1, flagged as W04, is seen only in 19–22 MeV protons. Increases in all particle species are seen for event 2, flagged as W07. Abundance ratios of both He/H and Fe/O rise initially in event 2, and Fe/O is strongly suppressed at low energies.

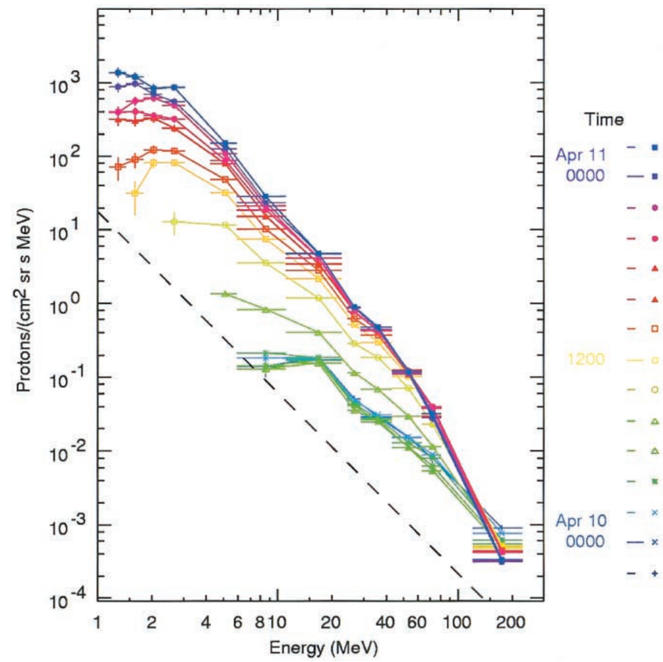

FIG. 2.—Proton energy spectra shown at 2 hr intervals from the 2200 UT on April 9 through 0200 UT on April 11, contrasting the hard spectra of event 1 with the softer but more intense spectra during event 2. Isotropic background prior to event 1, shown as a dashed line, has been subtracted from the other spectra.

Despite the behavior of He/H, however, in nearly all of the events we have observed, Fe/O at 2.5–10 MeV amu^{-1} begins at a high value and falls initially. This is not surprising. For $\mu \sim 1$, 2.5 MeV amu^{-1} O^{+6} will resonate with waves produced by 18 MeV protons while Fe^{+14} resonates with waves produced by ~40 MeV protons. It is usually unlikely that the high-energy proton spectra are sufficiently flat and that the intensities of 40 MeV protons are sufficiently high to grow enough waves in 1–2 hr that cause Fe to scatter more than O. At energies well below 1 MeV amu^{-1}, initially rising Fe/O may be much more common, but above ~2 MeV amu^{-1}, wave generation by protons from the same event cannot explain this behavior.

2. THE EVENTS OF 2001 APRIL 9 AND 10

We consider two SEP events in this Letter. Event 1 is associated with an M7.9 X-ray event that began at 1520 UT on 2001 April 9, a 2B flare at S21°W04°, and an 1192 km s^{-1} CME observed at 1554 UT. Event 2 is associated with an X2.3 X-ray event that began at 0506 UT on 2001 April 10, a 3B flare at S23°W09°, and a 2411 km s^{-1} CME observed at 0530 UT. Both events were observed by the proton detectors on NOAA/*GOES* as well as those on the *Wind* and *IMP-8* spacecraft. Event 1 had peak proton fluxes at greater than 10 MeV and greater than 100 MeV of 5 and 0.4 (cm^2 sr s)$^{-1}$, respectively, a very hard spectrum. For event 2, the corresponding fluxes were 300 and 0.3 (cm^2 sr s)$^{-1}$. Shock waves from the two events arrived on April 11 at about 1410 and 1430 UT; their order of association is uncertain.

Figure 1 shows intensities of various ion species and abundance ratios observed during this period on the *Wind* and *IMP-8* spacecraft (see von Rosenvinge et al. 1995). The onset of event 1 is seen only in the 19–22 MeV protons in this figure; the event is not observed in any of the other ion channels. Event 2 shows a clear onset in all channels, and the intensities then rise to peaks after the time of passage of the shocks. Rising abundance ratios are seen in the figure during event 2 for both Fe/O and He/H. However, the early suppression of Fe/O is much stronger at 2.5–3.2 MeV amu^{-1} than at 5–10 MeV amu^{-1}.

The evolution of the proton spectra is shown at 2 hr intervals in Figure 2, with the isotropic background prior to event 1 (shown as a dashed line) subtracted. The spectra during event 1 are hard, but the intensities are quite low. During event 2, intensities rise by a factor of ~100 near 10 MeV, but they decrease slightly above 100 MeV.

3. DISCUSSION AND CONCLUSIONS

The proton spectra during event 1 are substantially harder in the 10–60 MeV region, where wave generation might affect the low-energy Fe/O ratios, than in the 1998 September 30 event considered by Reames et al. (2000) and Ng et al. (2001), for example. However, the intensities are a factor of ~50 lower, and even though the protons from event 1 have ~15 hr to generate waves prior to the arrival of Fe from event 2, wave generation far beyond the shock of event 1 is probably minimal.

The key to understanding the suppressed Fe/O during the first day of event 2 may be that these ions *must actually leak through the west flank of shock 1* on their way to Earth during this time. Perhaps the turbulence at this shock, and in the downstream region behind it, scatters and traps Fe more than O; this strongly suppresses Fe/O in those ions that leak through shock 1 and propagate out toward Earth. However, the process that produces such strong modulation of the 2.5–3.2 MeV amu^{-1} Fe/O is not fully understood. The suppression of Fe/O decreases with increasing energy because of the decreasing spectrum of the protons that generate fewer resonant waves; for example, waves that affect Fe^{+14} at 10 MeV amu^{-1} would be generated by scarce 150 MeV protons. He/H is less strongly affected since protons accelerated by shock 1 in the 5–10 MeV region barely rise above the preexisting isotropic background that provides a seed population.

It is also possible that protons from event 2 play some role in modifying the turbulence behind shock 1, since Fe/O is more strongly modulated than He/H, even when compared at nearly the same rigidities. At a given rigidity, and resonant wave-number, He has half the velocity, and Fe has $\sim\frac{1}{4}$ the velocity, of H. Therefore, the protons arrive first at a particular location, and they have a longer time to modify the wave spectrum to affect Fe than to affect either He or O. However, event 2 alone is not responsible for the strong suppression of Fe/O; there are many events, otherwise similar to event 2, that show no such suppression. The presence of shock 1 is an essential ingredient. Unfortunately, the two-shock configuration is too complex for current numerical models to accommodate.

Despite the complexity, the relative abundances of elements with different values of Q/A are powerful tools for probing the spatial and temporal variations in the spectra of interplanetary Alfvén waves that scatter them, especially in the range of 1–10 MeV amu^{-1}. At energies below ~1 MeV amu^{-1}, ion speeds are slow, and their abundances are easily affected by a complex spatial pattern of waves generated by $\leqslant$10 MeV protons that are often copious. Fe ions with energies above ~10 MeV amu^{-1} resonate with waves generated by protons of such high energy that their abundances are rarely influenced by protons from the same event, except in the immediate vicinity of the shock. Variations in Fe/O at high energies may also have other origins (e.g., Tylka et al. 2001).

In the intermediate region from 1 to 10 MeV amu^{-1}, abundance ratios often respond to wave spectra generated by 1–100 MeV protons from the same event, and, on some occasions, their trajectory to Earth traverses a residual wave spectrum left by an earlier event; such is the case presented herein. Another, less dramatic, example of rising Fe/O is seen in the 2000 July 14 "Bastille Day" event where, again, the ions must pass through an intervening shock wave (see Reames, Ng, & Tylka 2001). However, the SEP event of 2001 April 10 provides a uniquely clear example of abundance modulation associated with an intermediate interplanetary shock.

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