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HEAVY ION ABUNDANCES AND SPECTRA AND THE LARGE GRADUAL SOLAR ENERGETIC PARTICLE EVENT OF 2000 JULY 14

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ABSTRACT

We compare the spectra and abundances of heavy elements of atomic number Z in the range $34 \leq Z \leq 40$ with those of He, C, O, Ne, Si, and Fe, as observed on the *Wind* spacecraft, in the large solar energetic particle (SEP) events of 1998 April 20 and 2000 July 14. This is the first time that spectra of the rare, trans-Fe, $34 \leq Z \leq 40$ ions have been measured in SEP events. We use the systematic dependence of the spectral *e*-folding energies on the charge-to-mass ratio (Q/A) of the species to estimate ionization states of each species. Ionization states of $Q \sim 11$ for ions with $34 \leq Z \leq 40$ are comparable to those for Si and Fe.

Subject headings: acceleration of particles — shock waves — Sun: abundances — Sun: corona — Sun: particle emission

1. INTRODUCTION

In recent years, we have found that the particles in the large "gradual" solar energetic particle (SEP) events are accelerated by shock waves driven out from the Sun by fast coronal mass ejections (CMEs) and *not* by solar flares (Gosling 1993; Kahler 1994; Reames 1995, 1999; Lee 1983, 1997; Reames, Barbier, & Ng 1996). In contrast, those particles that *are* accelerated in flares have unusual abundance enhancements, relative to coronal abundances, by factors of ~1000 in ^{3}He/^{4}He and ~10 in Fe/O arising from resonant wave-particle interactions in the flare plasma (see review in Reames 1999). Recently, Reames (2000) has reported that the unusual abundance enhancements in flare-accelerated SEP events continue into the high-Z region with enhancements in ($34 \leq Z \leq 40$)/O and ($50 \leq Z \leq 56$)/O of ~100 and ~1000, respectively. Meanwhile, the large gradual events exhibit the same modest, time-dependent enhancements for $Z \geq 34$ ions (Reames 2000) that were observed for elements with $Z \leq 26$ (e.g., Tylka, Reames, & Ng 1999a, 1999b; Reames, Ng, & Tylka 2000).

In large gradual SEP events, the theory of self-generated waves has been employed to understand both the acceleration of the particles at interplanetary shock waves in time equilibrium (Lee 1983, 1997) and the transport of particles outward from a source near the Sun (Ng & Reames 1994; Reames & Ng 1998). Time variations of abundance in gradual events have been modeled theoretically by Ng, Reames, & Tylka (1999a, 1999b) in terms of the transport of ions away from the shock through proton-generated waves that vary in space and time.

At some high energy, intensities of streaming protons are no longer sufficient to generate the waves required to trap particles near the shock long enough for additional acceleration. Here the particles leak away and the energy spectra steepen. Ellison & Ramaty (1985) parameterized the shock spectrum as a power law times an exponential. Recently, Tylka et al. (2000) studied the species dependence of the *e*-folding energy for a wide variety of ions and found that the *e*-folding energy/nucleon E_0 scales as a power (~1) of the charge-to-mass ratio (Q/A) of the ion.

The large SEP event of 2000 July 14 provides a rare opportunity to study all of the features we have discussed above. This event is the largest of this solar cycle, comparable in intensities of 10–100 MeV protons to the large events of 1989 (Reames & Ng 1998). Thus, it also provides high intensities of the rare elements, such as those with $34 \leq Z \leq 40$, that provide leverage in measurements of Q/A dependences. Energy spectra of those ions are reported here, for the first time. Higher proton intensities also strain our theoretical understanding of the physics of wave generation and evolution. Yet the event has exponential spectra with *e*-folding energies located within our region of observation.

One price we pay for the high intensities is that many instruments that might extend the spectral energy coverage are saturated and unable to contribute. Thus, all spectra and abundances of elements with $Z > 1$ reported in this Letter come from the Low-Energy Matrix Telescope (LEMT) system of the Energetic Particles: Acceleration, Composition, and Transport (EPACT) experiment (von Rosenvinge et al. 1995) aboard the *Wind* spacecraft. Even for the LEMT, dead-time corrections could be more uncertain at very high proton intensities, and some accidental-coincidence background is seen at the lowest energies in the He pulse heights. In any case, *all abundances and spectra of ions with* $Z \geq 6$ *share a single overall normalization on the LEMT and are correct relative to one another*. The proton intensities considered here are derived from the NOAA/*GOES* spacecraft, which does not saturate in large events (see Reames & Ng 1998).

2. VARIATION OF ABUNDANCES WITH TIME

Figure 1 compares the intensity-time profiles for protons and the abundance variations for heavy ions for the 1998 April 20 and 2000 July 14 SEP events. The event source longitudes, at W90° and W07°, respectively, are initially on opposite sides of the nominal magnetic field line that is well connected to Earth at ~W55°. The CME speed in the 1989 April event is 1631 km s^{-1}; that in the July 14 event is greater than 1450 km s^{-1}. However, the July event evolves much more rapidly because the

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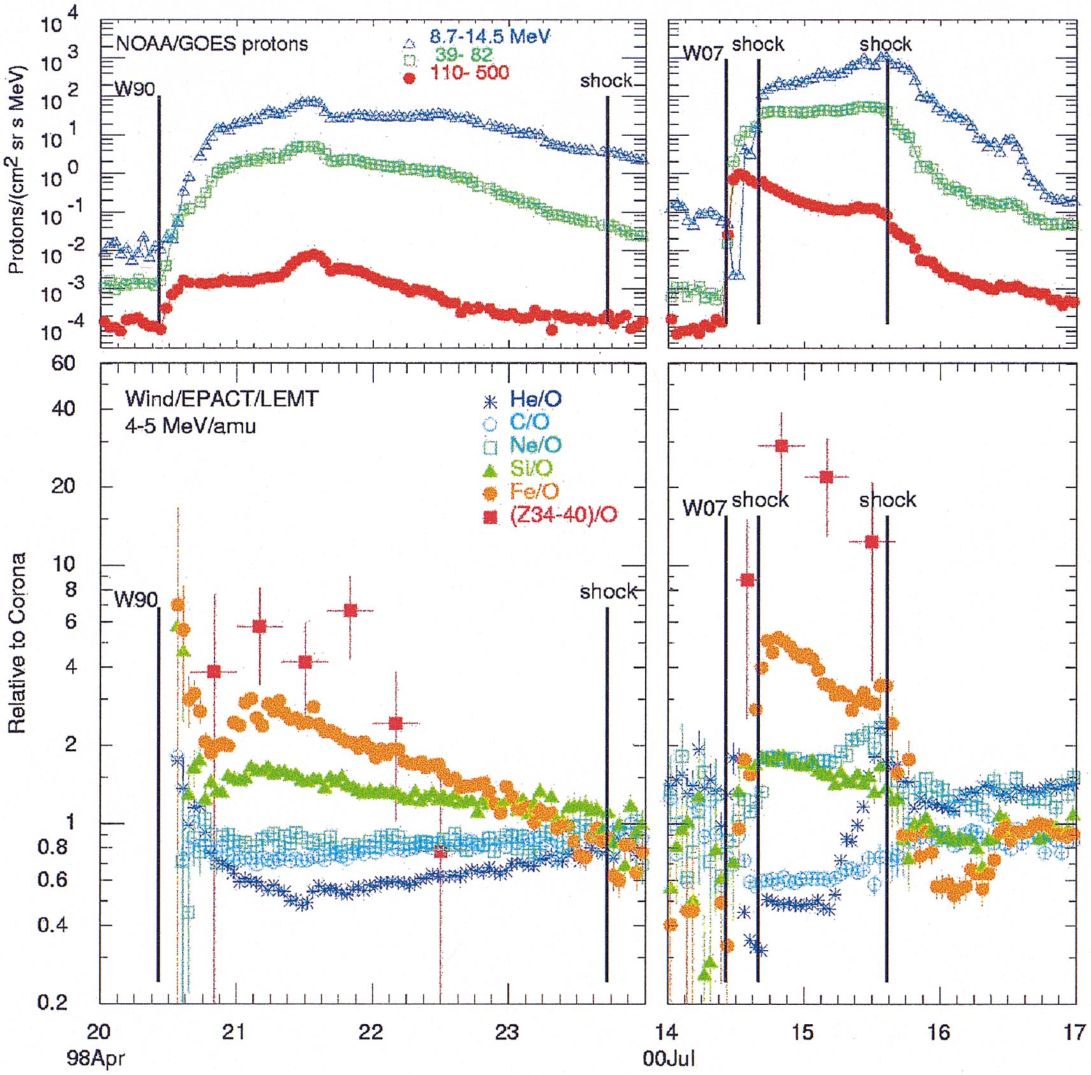

FIG. 1. Proton intensities (*top*) and relative abundances of ion species (*bottom*) vs. time compared for the 1998 April 20 and the 2000 July 14 SEP events

highest speed “nose” of that shock is directed toward Earth, while it is directed away from Earth in the 1998 April event.

Notice, also, the sharp jump in intensities of 8.7–14.5 and 39–82 MeV protons at the shock from an earlier event that arrives at Earth on July 14, only a few hours after the SEP onset. That shock appears to trap or reflect protons of these energies. The intensity of 39–82 MeV protons, trapped behind the early shock, jumps to a value ∼4 times higher than the streaming limit found for that energy (Reames & Ng 1998).

The general pattern of abundance variations, shown in Figure 1, is similar in the two events. With the exception of Ne, the ordering of the peak enhancement or the suppression of ion abundances is the same in the 1998 April event as it is in the 2000 July event. However, Ne/O changes from being suppressed like C/O in the April event to being enhanced like Si in the July event. Since abundance variations generally increase with decreasing Q/A (Ng et al. 1999a, 1999b; Tylka et al. 1999a), we would expect the Q/A of Ne (and possibly also Fe and $34 \leq Z \leq 40$) ions to be *lower* relative to that of O in the July event than in the April event. The magnitude of the enhancements attenuates and even reverses behind the primary shock.

3. ENERGY SPECTRA

In a recent paper, Tylka et al. (2000) presented an extensive study of energy spectra, especially in the 1998 April event. They show that the observed spectra, unlike those at the shock, were flattened at low energies by transport. With the power-law dependence effectively removed by transport, the spectra were almost purely exponential in form. In order to include the spectrum of $34 \leq Z \leq 40$ ions, we show spectra averaged over the day April 21 in Figure 2. The energy scale in the figure is linear, so the slope of the least-squares fit lines shown in the figure is $(E_0)^{-1}$. Fits to the exponential form were determined using LEMT intensities weighted in the usual way by their statistical errors. For $Z \leq 26$, Tylka et al. (2000) show fits for a larger spectral region using data from other spacecraft in this event.

Figure 3 shows spectra during the 2000 July event, averaged over three 8 hr periods beginning at the times shown. As in the April event, the spectra here are reasonably well fitted to the exponential form. For He in the left panel of the figure, the flat spectrum suggests that E_0 may be well above the mea-

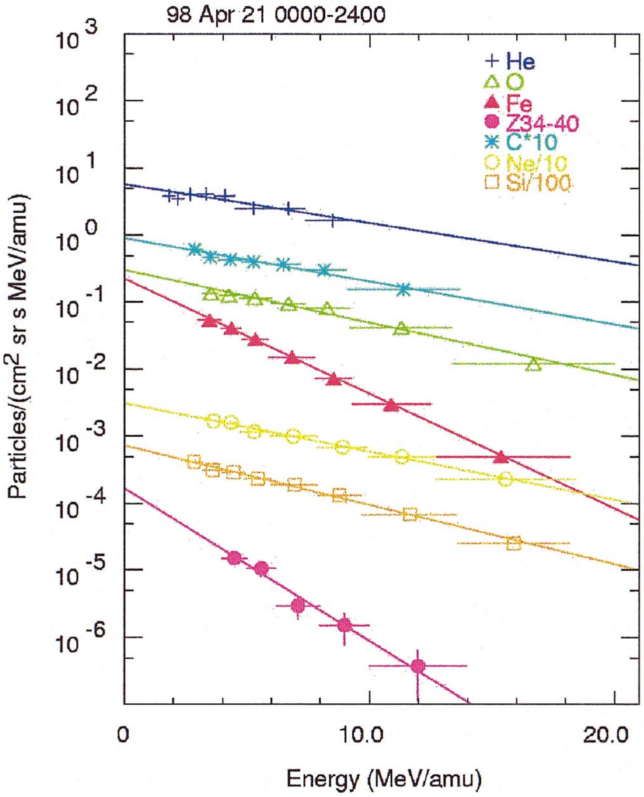

FIG. 2. Energy spectra for several ion species shown during the day of 1998 April 21. Least-squares fit lines appropriate for exponential spectra are shown. Note the linear energy scale.

surement region. In addition, in the right panel, the spectral slope for the ions with $34 \leq Z \leq 40$ is poorly defined.

We have used *e*-folding energies determined from these spectral fits to estimate ionization states for the elements. Extrapolating from the theory of Ellison & Ramaty (1985), Tylka et al. (2000) assumed that $E_0(Z) = (Q/A)^\delta E_0(\text{proton})$ to derive ionization states in the 1998 April 20 event. They were able to determine that $\delta = 1.0$ for this event from the highly precise H and He spectra from *IMP-8* and *Wind* (these two spacecraft normally provide 47 differential energy bins of H and He above 1 MeV amu^{-1}), although higher values of δ were found in the 1998 August 24 event, for example. We can confidently and easily extend the measurements of Q in the 1998 April event to the $34 \leq Z \leq 40$ ions using $\delta = 1.0$. The resulting values of Q are plotted versus Z in Figure 4.

For the 2000 July event, instrument saturation denies us the reliable high-resolution proton spectra from the *IMP-8* spacecraft, and our He spectra from LEMT suffer from problems of background at low energies late in the event. For that reason, we normalize the ionization states by arbitrarily assuming that $Q(\text{C}) = 5.5$ and show the derived values of Q for other species by assuming that $\delta = 1.0$ and $\delta = 1.5$ in Figure 4. While we cannot exclude higher values of δ, which would imply higher Q-values especially for $Z \geq 26$, in the July event, the similarity of the general pattern of abundance behavior in both events suggests that $\delta = 1$ is quite possible for the July event as well as the April event.

Note, however, that certain patterns, such as the relative Q/A-values for O and Ne, are especially insensitive to δ and still differ in the two events. We drew a similar conclusion from the higher Ne enhancement for July in Figure 1. A higher

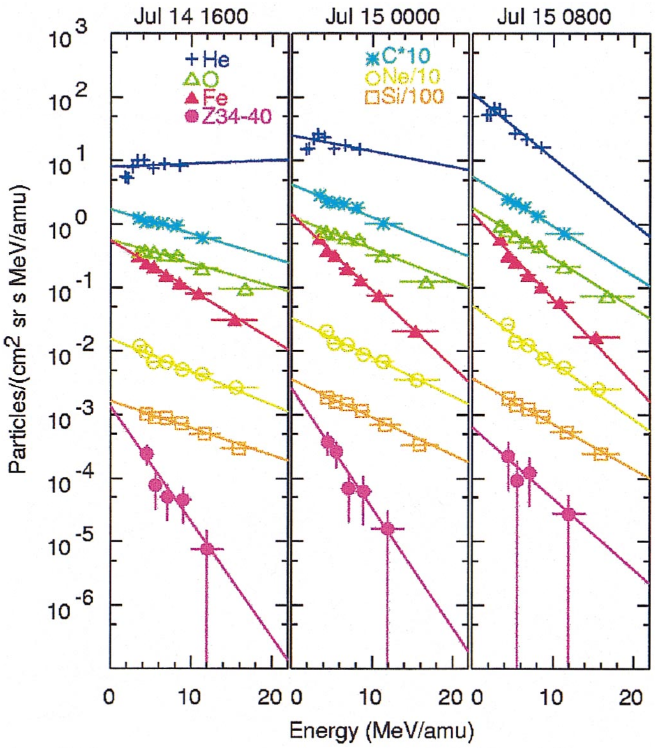

FIG. 3. Energy spectra for several ion species shown for three 8 hr intervals, beginning at the times listed, during the 2000 July 14 SEP event. Least-squares fit lines appropriate for exponential spectra are shown. Note the linear energy scale.

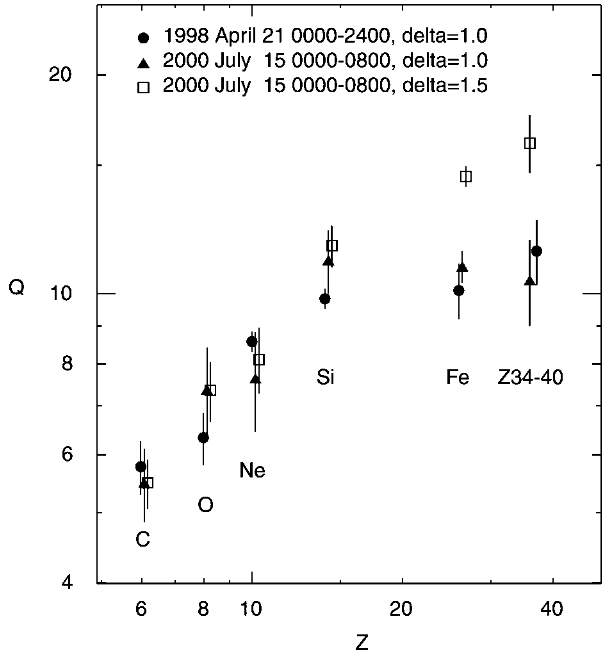

FIG. 4. Ionization states estimated for various elements from spectral *e*-folding energies E_0 during the 1998 April 20 and 2000 July 14 events (see text).

Q/A for O in July is also consistent with the magnified enhancement of Fe/O and ($34 \leq Z \leq 40$)/O since it changes the reference Q/A in these ratios. Thus, the ionization states derived from the *e*-folding energies are consistent with our expectations from the abundance enhancements in the previous section.

Some of the spectra in Figure 3, especially O, show evidence of a roll-off at high energy that indicates some departure from a purely exponential form. This could cause additional uncertainty in the determination of ionization states in the 2000 July event. However, we note that the progressive steepening in the slopes, as we go from C to Si to Fe to ($34 \leq Z \leq 40$), is extremely well defined within our energy interval. The differences in slopes and Q/A between Fe and ($34 \leq Z \leq 40$) ions can be explained by the differences in A alone. While the spectra of Ellison & Ramaty (1985) may be valid at a single shock, the effects of trapping and energy-dependent filtration of the spectra between the two (July 14 and 15) shocks could clearly alter the spectral shapes. Under these conditions, perhaps we should be surprised that the spectra are as close to exponential as they are and that they allow any solution for the ionization states in the 2000 July event that comes close to the well-determined ionization states in the 1998 April event.

4. CONCLUDING REMARKS

We have reported measured energy spectra of ions with $34 \leq Z \leq 40$ in large gradual SEP events for the first time. We have also used the systematic dependence of *e*-folding energy E_0 on Q/A of all ions to estimate ionization states of ions with $6 \leq Z \leq 40$. While these ionization states differ somewhat between the two events studied, they are not inconsistent with the presumption of the shock acceleration of the ions from material at the temperature of ambient coronal plasma. The $34 \leq Z \leq 40$ ions, with $Q \approx 11$, are *not* highly ionized. In fact, all elements with $14 \leq Z \leq 40$ may be similarly ionized in these events.

Normally, the spectral *e*-folding energies would be considered as a property of the primary accelerating shock. However, for the 2000 July 14 event, trapping of particles behind the earlier shock may also be a factor. This may also be a factor in the radically different behavior in Fe/O, for example, seen in the July event from that in the 1998 August event (Tylka et al. 1999a; Reames 1999), which also has a source near the central meridian on the Sun. The 1998 August had suppressed values of Fe/O that decreased with time and *e*-folding energies for H and He that were related by a large value of δ.

The two SEP events of 1998 April and 2000 July flank the magnetically well-connected longitude. Charge states in the 1998 April event are clearly consistent with *no* stripping of ions after acceleration. Lack of stripping is also possible for the 2000 July event. Such stripping *has* been seen in the well-connected SEP event of 1997 November 6 (Reames, Ng, & Tylka 1999). Perhaps it is only in well-connected events that we see ions accelerated sufficiently low in the corona where ambient densities are adequate to produce the distinctive signature of post–accelerative stripping.

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