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ABUNDANCES OF TRANS-IRON ELEMENTS IN SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

We report the first comprehensive observation of the abundances of heavy elements of atomic number Z in the range $34 \le Z \le 82$ in solar energetic particle (SEP) events as observed on the *Wind* spacecraft. In large gradual SEP events, abundances of the element groups $34 \le Z \le 40$, $50 \le Z \le 56$, and $70 \le Z \le 82$, relative to Fe, are similar to corresponding coronal abundances within a factor of ~2 and vary little with time during the events. However, in sharp contrast, abundances of these ions from impulsive flares increase dramatically with Z so that abundances of Fe, $34 \le Z \le 40$, and $50 \le Z \le 56$, relative to O, are seen at ~10, ~100, and ~1000 times their coronal values, respectively.

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

1. INTRODUCTION

In recent years it has become clear that the particles in the large "gradual" solar energetic particle (SEP) events are accelerated at shock waves driven out from the Sun by fast coronal mass ejections (CMEs) and *not* in solar flares (Gosling 1993; Kahler 1994; Reames 1999). Meanwhile, the particles that *are* accelerated in impulsive flares are characterized by dramatic abundance enhancements by factors of ~1000 in $^3He/^4He$ and ~10 in Fe/O that are believed to arise from resonant wave-particle interactions in the flare plasma (Roth & Temerin 1997; Miller & Reames 1996). Similar abundance enhancements in flare-accelerated ions are also deduced from gamma-ray line observations of flares (e.g., Mandzhavidze, Ramaty, & Kozlovsky 1999). The degree of heavy-element enhancement generally increases with Z in impulsive SEP events (e.g., Reames, Meyer, & von Rosenvinge 1994) but undergoes a more modest increase or decrease with Z in gradual SEP events (Breneman & Stone 1985; Tylka, Reames, & Ng 1999; Ng, Reames, & Tylka 1999a, 1999b; Reames 1999).

Because of the precipitous decline in solar abundances of elements above Fe, nearly all of our previous information on the behavior of SEP abundances came from the first ~30 elements of the periodic table, leaving two-thirds of this territory largely unexplored. Heavy elements with $34 \le Z \le 82$ cover a broader range of parameter space in the study of both resonant acceleration in flares and resonant scattering during particle acceleration and transport from shocks. All these processes depend upon the charge-to-mass ratio Q/A of the particles.

The only previous report of abundances of trans-Fe elements in SEP events was a measurement of particle tracks in a glass window of the *Apollo 16* command module (Shirk & Price 1973) attributed to the large 1972 April 18 event that occurred 2 days after launch. That single observation found a ~1000-fold enhancement in $(Z > 44)$/He, relative to solar abundances available at that time. In the present Letter, we report results of the first comprehensive observation of the abundances of elements with $34 \le Z \le 82$ in both gradual and impulsive SEP events as measured on board the *Wind* spacecraft during the first ~5 years of its mission.

2. EXPERIMENT TECHNIQUE

All SEP observations reported in this Letter were measured with the Energetic Particles: Acceleration, Composition, and Transport (EPACT) experiment (von Rosenvinge et al. 1995) on board the *Wind* spacecraft launched 1994 November 1. The Low-Energy Matrix Telescope (LEMT) system on EPACT consists of three individual telescopes of Si solid-state detectors using the dE/dx versus E technique for particle identification and measurement. Each telescope consists of a domed array of 16 detectors nominally 17 μm in thickness (D detector) followed by a large 1 mm thick position-sensing strip detector (E detector) and an anticoincidence detector. With a total collecting geometry factor of 51 cm^2 sr and a large dynamic range above ~2 MeV amu^{-1}, LEMT is ideal for heavy-element detection. However, it was specifically designed for exploratory measurements, and individual element resolution was deliberately sacrificed to press the large geometry factor to the lowest possible energy. LEMT was calibrated for high Z at low energy using beams of 550 MeV ^{197}Au, ^{107}Ag, and ^{56}Fe at the Holifield Heavy Ion Research Facility in Oak Ridge, Tennessee, as described in von Rosenvinge et al. (1995). Other papers show the resolution and in-flight results from LEMT for the ions H through Fe from various sources (see Reames 1999).

LEMT response in the high-Z region for the entire study period from 1994 November 3 to 2000 May 14 is shown in Figure 1. Particles are plotted or binned according to their energy deposit in the D and E detectors. LEMT can measure and process particles at a rate of ~36,000 s^{-1}, identifying and binning them by species and energy on board below $Z \sim 30$. However, the telemetry allows pulse-height measurements at a rate of only ~1 particle s^{-1} to be sampled and sent to the ground for further analysis. To ensure that the rare high-Z particles are sampled, about 6% of the pulse-height telemetry space is reserved for particles identified as having $Z > 33$ by the onboard algorithm. This priority boundary is shown in Figure 1. Also shown are calibration curves for the 3.3–10 MeV amu^{-1} study region for even-Z elements up to $Z = 60$ and selected elements thereafter.

The element resolution of LEMT is limited by thickness variations across the thin dome detectors and residual uncorrected variations in path length through these detectors. Thus, the spread in the dome energy deposit D is approximately a constant percentage of the signal. However, the spacing of the element dE/dx decreases with Z so that the variance σ_Z increases from ~0.9 units at $Z = 26$ to ~2.5 units at $Z = 60$. The distribution of measured Z, in the 3.3–10 MeV amu^{-1} region, is shown in Figure 2 binned in 0.2 units of Z.

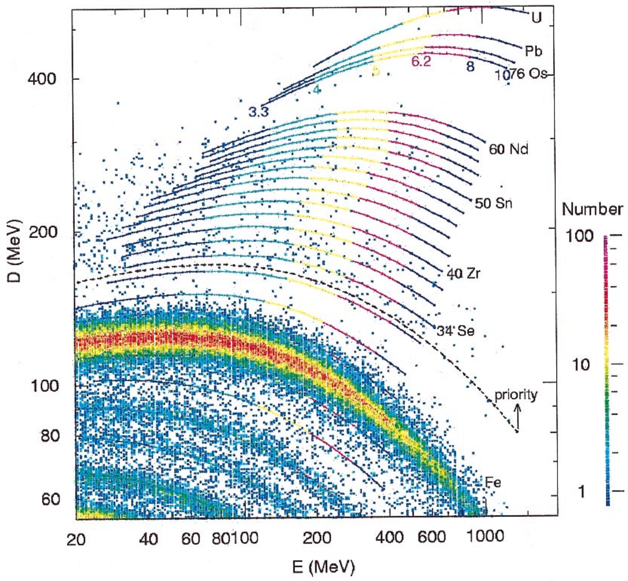

FIG. 1.—Distribution of particles with energy deposited in the dome (D) detector vs. that in the energy (E) detector of the LEMT telescope for the first 5.5 years of the *Wind* mission. Calibration curves identify selected elements.

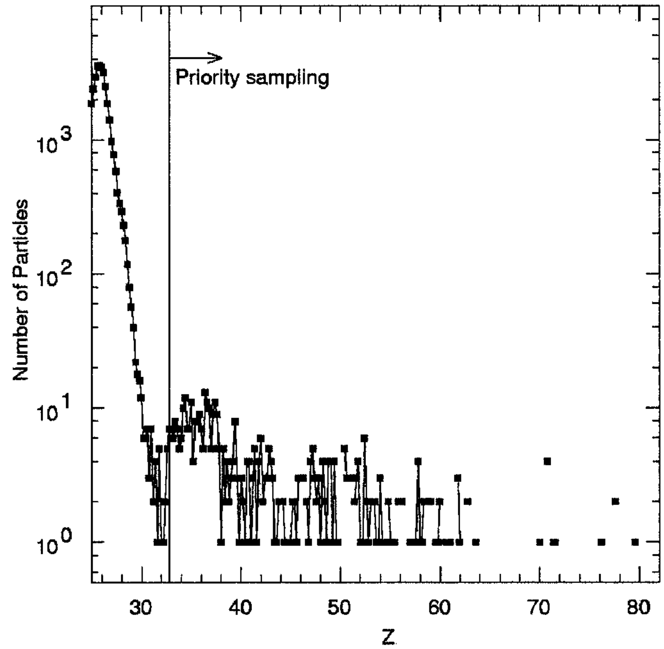

FIG. 2.—A histogram shows the number of particles vs. Z binned in 0.2 units of Z for all particles in the 3.3–10 MeV amu^{-1} interval.

Concerning the possibility of background that might contribute to the trans-Fe abundances, we note the following: (1) Trans-Fe ions are observed only in SEP events, not during quiet times as might be the case for any fragmentation produced by galactic cosmic rays. Fragmentation is highly unlikely in the thin, 17 μm, front detectors, as is the production of $Z > 33$ fragments. (2) We will see that the highest Z ions are associated with small impulsive flare events, where intensities are low, and not the large, intense SEP events, where accidental coincidences might be greater. (3) Accidental coincidences vary as the square of the particle intensities; no such behavior is observed for the trans-Fe ions. (4) Gaps in the pattern of abundances versus Z, seen in Figures 1 and 2, are not inconsistent with those expected from solar abundances, given the instrument resolution σ_Z. (5) The instrument was calibrated with intense ^{197}Au, ^{107}Ag, and ^{56}Fe accelerator beams; no nonlinear behavior was seen.

3. TRANS-IRON ELEMENT ABUNDANCES

Since the LEMT resolution is not adequate to resolve individual elements, we focus on three element groups: $34 \leq Z \leq 40$, $50 \leq Z \leq 56$, and $70 \leq Z \leq 82$. These groups correspond to islands of relatively high abundance in the solar abundance scheme (Grevesse & Sauval 1998). We have used the meteoritic abundances from Grevesse & Sauval (1998) to derive "coronal" abundances of these groups, decreasing the meteoritic abundance of the element Kr with its high first ionization potential by a factor of 4. Our derived coronal abundances of the three element groups, relative to Fe, are 1.66×10^{-4}, 2.16×10^{-5}, and 8.2×10^{-6}, respectively. For Fe/O, we use a coronal abundance ratio of 0.134 (Reames 1999). All abundance ratios are expressed relative to these coronal values.

Table 1 shows abundances of elements in large, well-studied SEP events with fast CME associations and in smaller events that are Fe-rich or ^{3}He-rich (^{3}He/^{4}He > 0.1), associated with flares with no accompanying fast CME. The times listed in Table 1 are the beginning times of the event averaging; for the large events, intensities were averaged for 1–2 days covering maximum intensity, depending on event duration, while in small events averaging continued for the duration of the event or until the onset of a subsequent event.

3.1. *Gradual Events*

For the large events listed in Table 1, the $(34 \leq Z \leq 40)$/Fe abundance is generally well measured. The enhancements in this ratio are quite modest and are smaller than the enhancements in Fe/O. In the very large 1998 August 25 event, with its small value of Fe/O, only one heavy ion is seen, although this is consistent with coronal abundances. Elements with $Z \geq 50$ are sparse in the large events, but, as at lower Z, there is no evidence whatsoever of large enhancements.

Several of the large events have sufficiently high intensities of ions with $34 \leq Z \leq 40$ that we can examine their time and energy dependence during the event. Figure 3 shows the intensity-time profiles of several species during the events of 1997 November 4 and 6. There is no evidence of unusual temporal behavior of the ions with $Z \geq 34$ in these events or in most other large events.

3.2. *Impulsive Events*

Heavy ions in the smaller events listed in Table 1 show a more striking behavior. The ratios $(34 \leq Z \leq 40)$/Fe and $(50 \leq Z \leq 56)$/Fe are sometimes enhanced by factors of ~10 and ~100, respectively. In fact, if we compare all of these abundances to O, the ratios Fe/O, $(34 \leq Z \leq 40)$/O, $(50 \leq Z \leq 56)$/O are enhanced by factors of ~10, ~100, and ~1000, respectively, relative to coronal values. In addition, most of the ions identified as $Z \geq 70$ that arrive during the 5.5 yr study period are seen during these few impulsive events. These enhancements in $(Z \geq 50)$/O are as large as those often seen in ^{3}He/^{4}He!

The series of impulsive flare events during 1998 September 26–29 is especially striking, as shown in Figure 4. Hα onset

TABLE 1
RELATIVE ABUNDANCES OF 3.3–10 MeV amu^{-1} IONS

Begin Time	Fe/O[a]	$(34 \le Z \le 40)$/Fe[a]	$(50 \le Z \le 56)$/Fe[a]	$(70 \le Z \le 82)$/Fe[a]	Peak Fe Intensity (m^2 sr s MeV)$^{-1}$
Large Events					
1997 Nov 7 0000	3.10 ± 0.017	2.07 ± 0.37	2.5 ± 1.1	<1.4	300
1998 Apr 21 0000	2.25 ± 0.006	1.96 ± 0.19	0.29 ± 0.20	<0.4	950
1998 May 2 1200	4.98 ± 0.12	2.8 ± 1.6	21 ± 12	<21	20
1998 May 6 0800	4.70 ± 0.065	1.51 ± 0.76	5.8 ± 4.1	7 ± 7	80
1998 Aug 25 0000	0.406 ± 0.005	0.48 ± 0.48	<3.7	<10	200
1998 Sep 30 0000	1.62 ± 0.009	1.51 ± 0.33	1.6 ± 1.0	<1.6	800
1998 Nov 14 0800	3.62 ± 0.029	1.82 ± 0.45	2.6 ± 1.5	2.3 ± 2.3	80
Fe-rich Impulsive Events					
1997 Sep 18 0000[b]	5.85 ± 0.31	6.7 ± 6.7	51 ± 51	<133	2
1998 Sep 6 1200	11.7 ± 0.98	18 ± 13	141 ± 100	<185	1
1998 Sep 26 1700[b]	8.9 ± 0.5	11 ± 8	130 ± 75	<114	8
1998 Sep 27 0900	6.0 ± 0.2	10 ± 5	165 ± 55	145 ± 84	20
1998 Sep 27 1800	10.2 ± 0.4	11 ± 6	195 ± 65	<57	22
1998 Sep 28 0000	11.1 ± 0.4	7 ± 4	17 ± 17	47 ± 47	20
1998 Sep 28 0800	11.8 ± 0.5	11 ± 5	62 ± 36	54 ± 54	10
1999 Aug 7 1800[b]	8.57 ± 1.5	<68	1040 ± 745	<1400	1
2000 May 1 1200	16.6 ± 0.72	<2.2	50 ± 29	<44	25

[a] Relative to coronal abundances.
[b] ^{3}He-rich events.

times and X-ray intensities for a series of flares from active region 8340 are shown in the figure. The flares are accompanied by type III and V radio emission. This series occurs following the 1 AU passage of a moderately large CME and associated SEP event that still dominates the low-energy H intensity. However, new increases in Fe are clearly seen following each new flare, and an increase in 18–20 MeV protons follows the W48 event at 0806 UT on September 27. Many of the $Z \ge 34$ ions cluster near the peak of this one event and half of the $Z \ge 70$ ions we observe on *Wind* arrive during this 3 day period. These impulsive events contrast with the large CME-associated event that begins on September 30 in Figure 4; despite its huge increase in Fe, it shows far fewer $Z \ge 50$ ions than the impulsive events that precede it.

4. DISCUSSION AND CONCLUSIONS

Measurement of the abundances of heavy elements with $34 \le Z \le 82$ provides new leverage for understanding the phys-

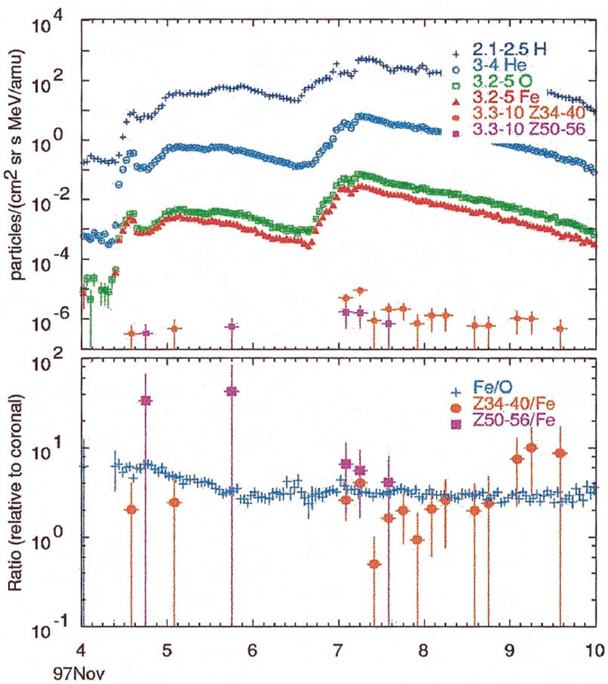

FIG. 3.—Intensities and abundance ratios vs. time for various species in the large 1997 November 6 event.

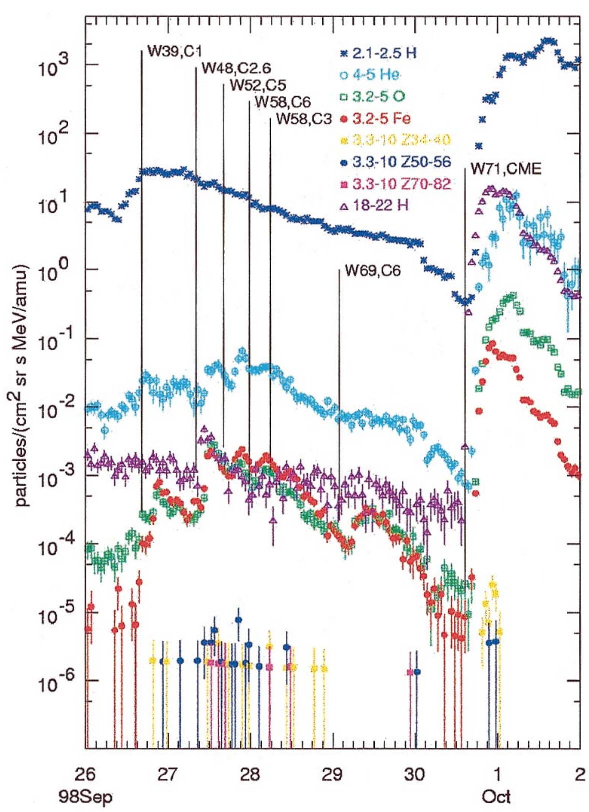

FIG. 4.—Intensities of various species vs. time during a series of impulsive flare injections at the times indicated during 1998 September 26–29, each followed by an increase in Fe. High-*Z* ion intensities from these small flares contrast with those from the large gradual (CME) event beginning September 30.

ical processes of particle acceleration at shock waves and in flares. The lack of any substantial enhancement or suppression of heavy ions in large gradual events suggests that their transport away from the shock is similar to that of Fe. In some cases, such as the 1998 April and August events, the high-energy spectral knee for the highest Z (lowest Q/A) ions may occur at sufficiently low energy that their intensities are suppressed (see Tylka et al. 2000). Event-averaged spectra in the 1998 April event for Fe and $34 \leq Z \leq 40$ are well fit to an exponential form with e-folding ("knee") energies of 2.43 ± 0.02 and 1.72 ± 0.13 MeV amu^{-1}, respectively. Extending the analysis of Tylka et al. (2000), we deduce that $Q/A = 0.14 \pm 0.01$ for the $34 \leq Z \leq 40$ group in this event.

For impulsive events, enhancements in $(50 \leq Z \leq 56)$/O of $\sim$100 and $(Z \geq 50)$/O of $\sim$1000, relative to coronal abundances, dramatically continue the progression of heavy-element enhancements above Fe. Qualitatively, this progression seems to argue for a cascading wave model of resonant stochastic acceleration in flares (e.g., Miller & Reames 1996). In this model, waves not absorbed by species at the lowest value of Q/A continue to cascade to increasingly high wavenumber, where they resonate with ions of higher gyrofrequency (higher Q/A) until they are eventually absorbed on He or H. The highest Z ions with the lowest initial Q are most strongly enhanced before they eventually become ionized later when the bulk plasma is heated (Reames et al. 1994; Reames 1999).

If we revisit the result of Shirk & Price (1973), using more recent abundances would imply an enhancement of $\sim$180 for their $(Z > 44)$/Fe measurement. This is more characteristic of our small impulsive events than the large gradual event of 1972 April 18 that occurred during *Apollo 16*. Given our spectral study, it is possible that still greater enhancements occur at the lower energies less than 0.5 MeV amu^{-1} that are observed on *Apollo 16* in large gradual SEP events. It is also possible that the $Z > 44$ ions actually came from impulsive flare events later in the *Apollo 16* mission.

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