SOLAR ENERGETIC PARTICLES: SAMPLING CORONAL ABUNDANCES

DONALD V. REAMES

NASA/ Goddard Space Flight Center, Greenbelt, MD 20771, USA

Abstract. In the large solar energetic particle (SEP) events, coronal mass ejections (CMEs) drive shock waves out through the corona that accelerate elements of the ambient material to MeV energies in a fairly democratic, temperature-independent manner. These events provide the most complete source of information on element abundances in the corona. Relative abundances of 22 elements from H through Zn display the well-known dependence on the first ionization potential (FIP) that distinguishes coronal and photospheric material. For most elements, the main abundance variations depend upon the gyrofrequency, and hence on the charge-to-mass ratio, Q/A, of the ion. Abundance variations in the dominant species, H and He, are not Q/A dependent, presumably because of nonlinear wave-particle interactions of H and He during acceleration. Impulsive flares provide a different sample of material that confirms the Ne:Mg:Si and He/C abundances in the corona.

1. Introduction

It is rather surprising that the most complete measurements of element abundances in the solar corona do not come from photons from the coronal plasma. They come from measurements of high-energy particles accelerated in the large solar energetic particle (SEP) events. The comparison of element abundances in SEP events with corresponding abundances in the photosphere led to the well-known dependence on the first ionization potential (FIP) of the elements (see *e.g.* Meyer 1985, 1993, 1996 and references therein). In fact, it is especially ironic that this "FIP effect" was sought for elements in the SEP events because a similar effect had been observed much earlier in the energetic particles of the galactic cosmic rays.

Initially it was thought that the energetic particles in the large SEP events were accelerated in solar flares. In recent years, however, it has become clear that in the large "gradual" events, particles are accelerated at shock waves that are driven out from the Sun by coronal mass ejections (CMEs) (Reames 1990, 1993, 1995b, 1997; Kahler 1992, 1994; Gosling 1993; Cliver 1996). We will see that these shocks accelerate the ions of the chemical elements in a fairly democratic manner. In contrast, the particles that are accelerated in impulsive solar flares have 1000-fold enhancements in the isotope ^{3}He relative to ^{4}He and enhancements of ~10 in heavy elements like Fe/O. These enhancements are believed to result from resonant wave-particle interactions during stochastic acceleration of the ions from the flare plasma.

In this paper we will consider three different populations of energetic particles: 1) gradual SEP events, 2) impulsive flare events, and 3) particles from co-rotating

Space Science Reviews **85**: 327–340, 1998.

interaction regions (CIRs). Gradual SEP events provide the most extensive and complete abundance information. We will devote most of our attention to these events, to the physical processes involved, the abundances they provide, and the variations and uncertainties in interpreting them as "coronal." Impulsive events involve a different source and acceleration mechanism with well-defined coronal sites, and despite the enhancements, can give independent abundance information in specific cases, such as Ne/Mg/Si and He/C. In CIR events the acceleration occurs at heliospheric shocks from a high-speed solar-wind source. Knowing the abundances of both the solar wind and the energetic CIR ions allows us to investigate the shock acceleration mechanism and compare it to that involved in the gradual events. This paper intends to describe abundance observations and their variations and errors; it is not intended as an exhaustive review.

2. Gradual SEP Events

The earliest measurements of element abundances in SEP events were made on sounding rockets in the 1960s (Fichtel and Guss 1961; Bertsch, Fichtel, and Reames 1969). Over the next decades measurements gradually improved and it became clear that SEP abundances differed from those of the photosphere or meteorites in two primary ways (Meyer 1985; Brenneman and Stone 1985). First, there was a dependence on the charge-to-mass ratio, Q/A, of the ion that varied from event to event, and second, there was a persistent dependence of the abundances on FIP. The Q/A dependence was recognized to be a result of the acceleration of the ions that also varied with time and with the energy of observation (Mazur *et al.* 1992). The ions are highly ionized by a coronal electron temperature of ~2 MK (Luhn *et al.* 1985) at the time of acceleration. Thus, the FIP effect can only occur at a much earlier time and a much lower temperature when an ion-neutral separation is possible.

2.1 THE AVERAGED ABUNDANCES OF ELEMENTS

The effect of FIP on the element abundances of the SEPs is most clearly illustrated by simply accumulating the raw abundance measurements over many SEP events. Measurements of an ion entering a particle telescope consist of measuring the energy loss in a thin (dE) silicon detector together with the energy deposited in a second thicker (E) detector in which the particle stops. A typical plot of dE *vs.* E, with each particle plotted as a single point, is shown in Figure 1. Data for Figure 1 were accumulated over 49 gradual SEP events periods occurring during 14 years. Already in these "raw" data, it is apparent that the abundances of Ne, Mg, Si and Fe are all comparable, a characteristic feature of coronal abundances.

Element abundances have been derived from Figure 1 by using the instrument calibration to define the velocity or energy/nucleon along the track of each element and then simply counting the number of ions of each element within a fixed velocity interval (5 - 12 MeV/amu). The resultant SEP-coronal abundances are shown in Table 1. Combining these SEP abundances with the corresponding photospheric abundances of Grevesse, Noels, and Sauval (1996) also given in Table 1, we obtain the FIP plot shown in Figure 2.

The measured SEP abundances in this study (Reames 1995a) are in excellent agreement with those obtained 10 years earlier by Brenneman and Stone (1985) for a different sample of events observed by a different instrument on a different spacecraft. The SEP measurements are extremely stable and well determined within the stated errors. However, Brenneman and Stone used a wrong value for the photospheric abundance of Fe and were led to the erroneous conclusion that the SEP and coronal abundances were substantially different by ~50% in Fe/C (Garrard and Stone 1994).

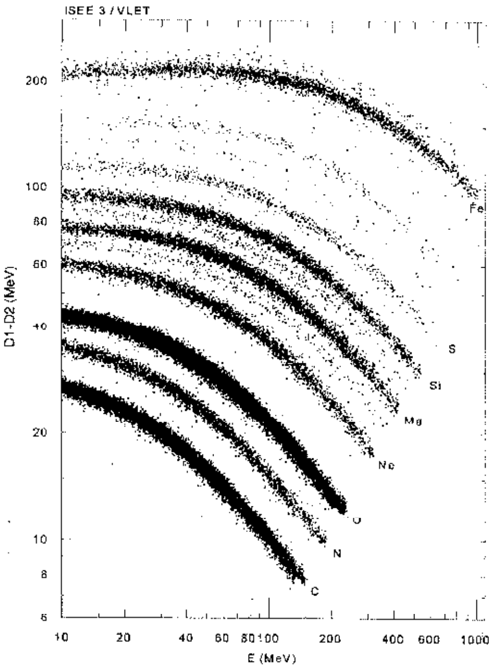

Fig. 1. Response of a detector to individual particles showing element resolution. Similar numbers of Ne, Mg, Si and Fe, typical of coronal abundances, are visible here in the raw data.

2.2 ACCELERATION

Shock acceleration is understood to occur when ions are scattered back and forth across the shock by scattering against magnetic turbulence (Alfvén waves) in the upstream and downstream regions. Because of the velocity discontinuity at the shock, the process can be viewed as scattering from "walls" that are approaching each other; ions receive an increment of velocity on each transit of the shock.

The interaction of a particle with electromagnetic fields is governed by the Lorentz equation, which may be written:

$$m_o \frac{d}{dt}(\gamma\, v) = \frac{Q}{A} e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{1}$$

Table 1. Element abundances in gradual SEP events and the photosphere.

	Z	FIP (eV)	SEP Corona (Gradual Events) (O=1000)	(dex)	Photosphere (dex)
H	1	13.527	(1.57±0.22)x10^6	12.07 ± 0.06	12.00 ± 0.0
He	2	24.46	57000 ± 3000	10.63 ± 0.023	10.99 ± 0.035
C	6	11.217	465 ± 9	8.54 ± 0.008	8.55 ± 0.05
N	7	14.48	124 ± 3	7.97 ± 0.010	7.97 ± 0.07
O	8	13.55	1000 ± 10	8.87 ± 0.004	8.87 ± 0.07
F	9	17.34	<0.1	<4.83	4.56 ± 0.3
Ne	10	21.47	152 ± 4	8.06 ± 0.011	8.08 ± 0.06
Na	11	5.12	10.4 ± 1.1	6.89 ± 0.046	6.33 ± 0.03
Mg	12	7.61	196 ± 4	8.17 ± 0.0089	7.58 ± 0.05
Al	13	5.96	15.7 ± 1.6	7.07 ± 0.044	6.47 ± 0.07
Si	14	8.12	152 ± 4	8.06 ± 0.011	7.55 ± 0.05
P	15	10.9	0.65± 0.17	5.69 ± 0.11	5.45 ± 0.04
S	16	10.3	31.8 ± 0.7	7.38 ± 0.0096	7.33 ± 0.11
Cl	17	12.952	0.24± 0.1	5.25 ± 0.18	5.5 ± 0.3
Ar	18	15.68	3.3 ± 0.2	6.39 ± 0.026	6.52 ± 0.10
K	19	4.318	0.55± 0.15	5.61 ± 0.12	5.12 ± 0.13
Ca	20	6.09	10.6 ± 0.4	6.90 ± 0.016	6.36 ± 0.02
Ti	22	6.81	0.34± 0.1	5.41 ± 0.13	5.02 ± 0.06
Cr	24	6.74	2.1 ± 0.3	6.20 ± 0.06	5.67 ± 0.03
Fe	26	7.83	134 ± 4	8.00 ± 0.013	7.50 ± 0.04
Ni	28	7.61	6.4 ± 0.6	6.68 ± 0.041	6.25 ± 0.01
Zn	30	9.36	0.11± 0.04	4.92 ± 0.16	4.60 ± 0.08

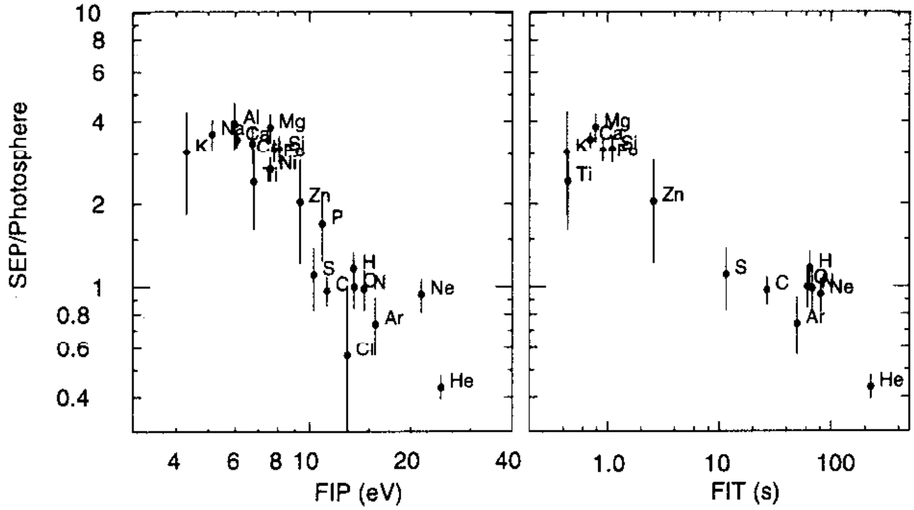

Fig. 2. Ratio of gradual SEP and photospheric abundances *vs.* first ionization potential (FIP) and *vs.* the first ionization time (FIT) of Marsch, von Steiger and Bochsler (1995).

where **E** and **B** are the electric and magnetic fields of the wave (or other accelerating fields), **v** is the ion velocity, Qe its charge, m_0A its mass, and γ is the Lorentz factor, $(1-v^2/c^2)^{-1/2}$. If the ions may be regarded as test particles that sample, but do not modify, the electromagnetic fields, then their behavior is completely described by two parameters, velocity and Q/A. According to equation (1), ions with the same value of Q/A are indistinguishable and will be accelerated identically. Since we always compare abundances in constant velocity intervals, Q/A is the only other variable that can distinguish different elements. Q/A determines the ion gyrofrequency and, hence, where it will interact with the wave-frequency spectrum.

However, before proceeding further, we should note that this simple picture is an approximation since the accelerated ions are *not* test particles. In fact, it is the H and He, streaming away from the shock that actually generate the waves that scatter subsequent particles (see *e.g.* Lee, 1983). Hence, it is unlikely that H and He abundances will depend solely on velocity and Q/A. Even the rarer elements can preferentially generate and absorb waves at their gyrofrequencies, modifying the electromagnetic environment slightly. However, we will see that variations in the abundances of the elements other than H and He are well described by Q/A.

Charge states of ions of the dominant elements from C through Fe were first measured in 12 large SEP events by Luhn *et al.* (1987). More recently, Boberg, Tylka and Adams (1996) summarized measurements of the ionization states of energetic Fe ions and compared them with measurements of Fe ions in the solar wind. They found that the ionization states of the accelerated Fe ions ($Q_{Fe} \sim 15$) are somewhat higher than those of the solar wind ($Q_{Fe} \sim 11$). The energetic Fe ion charges are similar to those of the solar wind plasma in the CME ejecta and in the sheath region that corresponds to coronal material swept up by the CME. This suggests that the "seed population" for the accelerated ions is coronal rather than solar wind material. Thus, coronal ions, initially accelerated to suprathermal speeds when the shock first encountered the base of each magnetic field line, continue to resupply the shock with "seed" particles as it moves outward along that flux tube.

2.3 ABUNDANCE VARIATIONS

We can use the measured ionization states of the elements to examine the Q/A-dependence of abundances in individual events. A plot of the relative enhancement of various elements *vs.* Q/A is shown for 3 events in Figure 3. The enhancements are relative to the average SEP corona given in the last section and Q/A is derived from measured values of Q of each element in each event (Luhn *et al.* 1985) at 0.3-2 MeV/amu. Two of the events shown in the figure, 1979 June 7 and 1978 September 23, represent the largest positive and negative slopes, respectively, of the 49 events studied (Reames 1995a). Note especially that C, N, O, Ne, and Mg usually have very similar values of Q/A, hence there is very little variation in the relative abundances of these elements. These elements are highly likely to exhibit the same abundances in SEP events that they had in the source plasma.

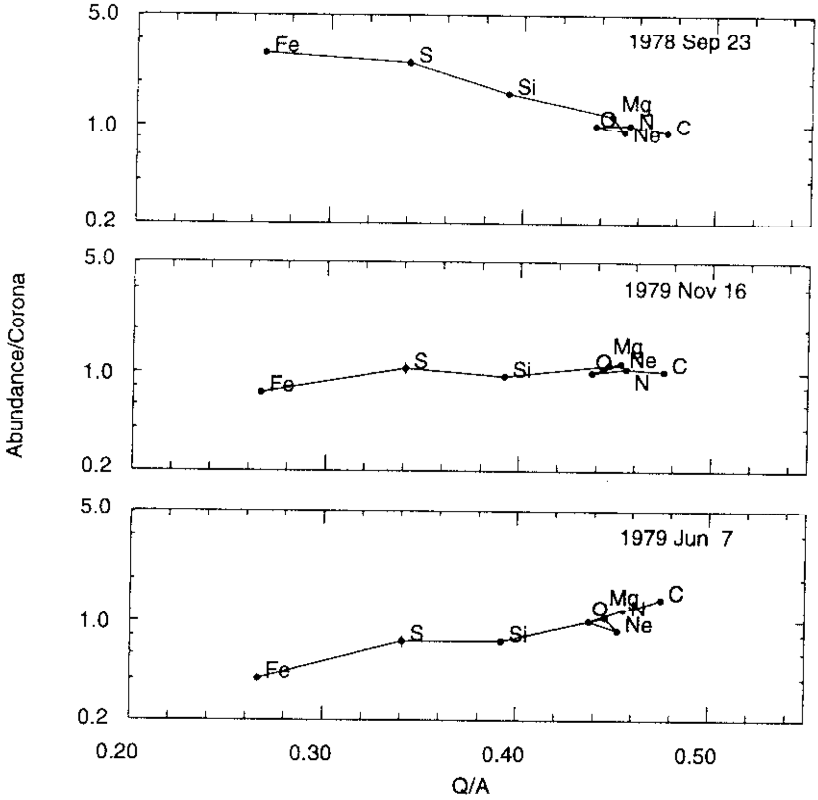

Fig. 3. *Q/A* dependence of the abundances in individual gradual SEP events relative to the corona. The upper and lower panels are the extreme values of 49 events that contributed to the 5-12 MeV/amu SEP average. The event in the middle panel is more typical. Note that the elements from C to Mg have similar values of *Q/A*.

It is a coincidence that the *Q/A* variations cancel when we sum over many events. That this is the case is shown by the close proximity of Fe to Mg and Si on the FIP plot in Figure 2; these three elements have similar values of FIP but much different values of *Q/A*. The average slope of the wave spectrum in the acceleration region affects the *Q/A* dependence. Ions of different *Q/A*, hence different gyrofrequencies, resonate with different parts of the wave frequency spectrum. The local slope of the wave frequency spectrum can thus determine the slope of the *Q/A* dependence. Of course, the ions can sample and average over a wide variety of conditions during the complete history of their acceleration.

There is some controversy as to whether a *Q/A* dependence like that shown in Figure 3 should be described as large or small. If we are allowed to fit smooth curves through the plots, changes of the charge state of Fe by a few units, for example, would change the observed abundance of Fe by ~20% in the worst case. For abundance measurements involving atomic spectral lines, changing the charge by a few units would make the line emission disappear completely. It is in this sense that we describe the SEP measurements as highly temperature insensitive and only weakly dependent on *Q/A*. However, Bochsler (1998, this volume) points out that the *Q/A* variations in the solar wind are much smaller than are those in SEP events. In fact, it is rather surprising that the more-modest acceleration of the solar wind produces a measurable *Q/A* dependence at all. A spectrum of Alfvén waves may be involved here as well.

When the enhancements are a smooth function of *Q/A*, and when each element's *Q/A* value varies little from event to event, another way to examine the dependence is by plotting ratios such as Si/O *vs.* Fe/O, for example. If Fe/O is enhanced or suppressed in a given event, Si/O is likely to follow proportionately. Such behavior is shown in the lower panels of Figure 4 where C/O and Si/O are highly correlated with Fe/O. In contrast, the upper 2 panels of the figure show little correlation between H/He or He/C and Fe/O. Clearly, the dominant elements, H and He, do not behave as test particles; they modify **E** and **B** in equation (1) in a nonlinear way and do not have the simple *Q/A* dependence of the heavier elements. The abundances of H and He depend upon the properties of the shock and on details of the particle and wave spectra.

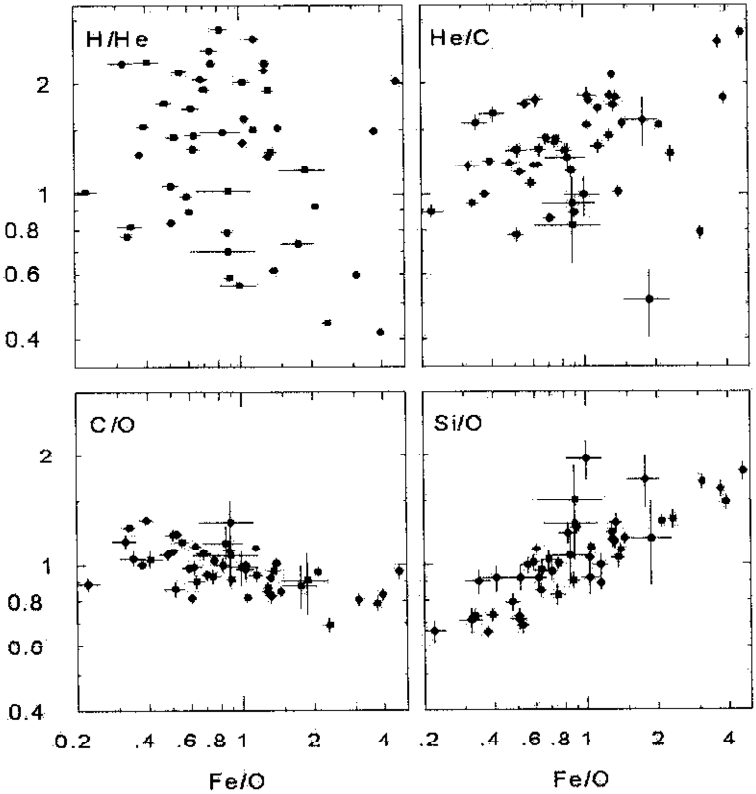

Fig. 4. Cross plots of H/He, He/C, C/O and Si/O relative to coronal values (Table 1) *vs.* Fe/O for 49 gradual SEP events at 1-4 MeV/amu for H/He and 5-12 MeV/amu otherwise (Reames 1995).

When we consider event-averaged data as shown in Figure 4, the scatter gives the impression of randomness in the variations that are independent of *Q/A*. In fact, early observers (Mason, Gloeckler, and Hovestadt 1984) thought that the time variations within an event were random, as the coronal shock crossed material with intrinsic abundance variations. However, more recent data, and especially new data from the Wind spacecraft, show that abundance variations with time are extremely systematic. Figure 5 shows data from the Wind spacecraft during the recent events associated with CMEs emitted on 1997 November 4 and 6 as marked by the vertical lines in the figure. The upper panel shows the intensity of 2.4–3.0 MeV/amu ^{4}He ions, while the lower panels show Fe/O and He/O in the same energy region. The event beginning on November 4 shows an Fe/O ratio that decreases smoothly with time while He/O remains constant. The classic *Q/A* variations we have seen before occur smoothly here within a single event. The event that begins on November 6 has a constant value of Fe/O, but He/O increases smoothly by a factor of ~2 over a 3-day period. These new measurements make it clear that abundance variations in SEP events are systematic, depending upon the physics of the acceleration, and are *not* random as was once thought.

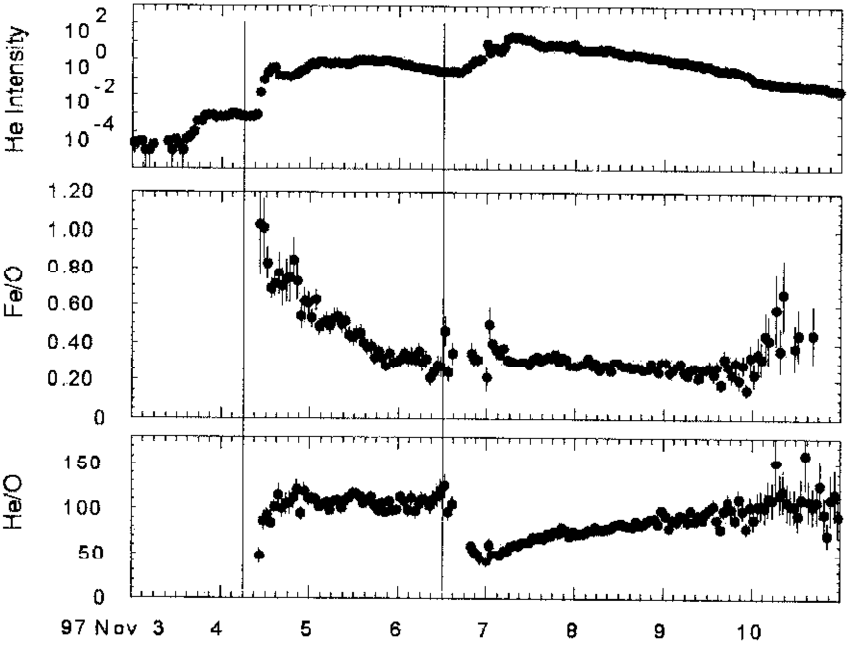

Fig. 5. Intensity of ^{4}He and Fe/O and He/O ratios during the 1997 November SEP events observed on the Wind spacecraft. During the event beginning on the 4th, Fe/O varies smoothly while He/O does not. For the event beginning on the 6th, He/O varies while Fe/O does not.

An example of even more spectacular systematic abundance variations during an event is provided by the 1998 April 20 event in Figure 6 (Tylka, Reames, and Ng 1998). Variations of this type can occur when wave generation at the shock leads to flattened spectra of the escaping ions at low energies. Ions with given velocity, v, but different Q/A resonate with different parts of the wave spectrum. The same variations in Q/A dependence that we saw in individual events (*e.g.* Figure 3) can now be seen to occur systematically with time during a single event as the

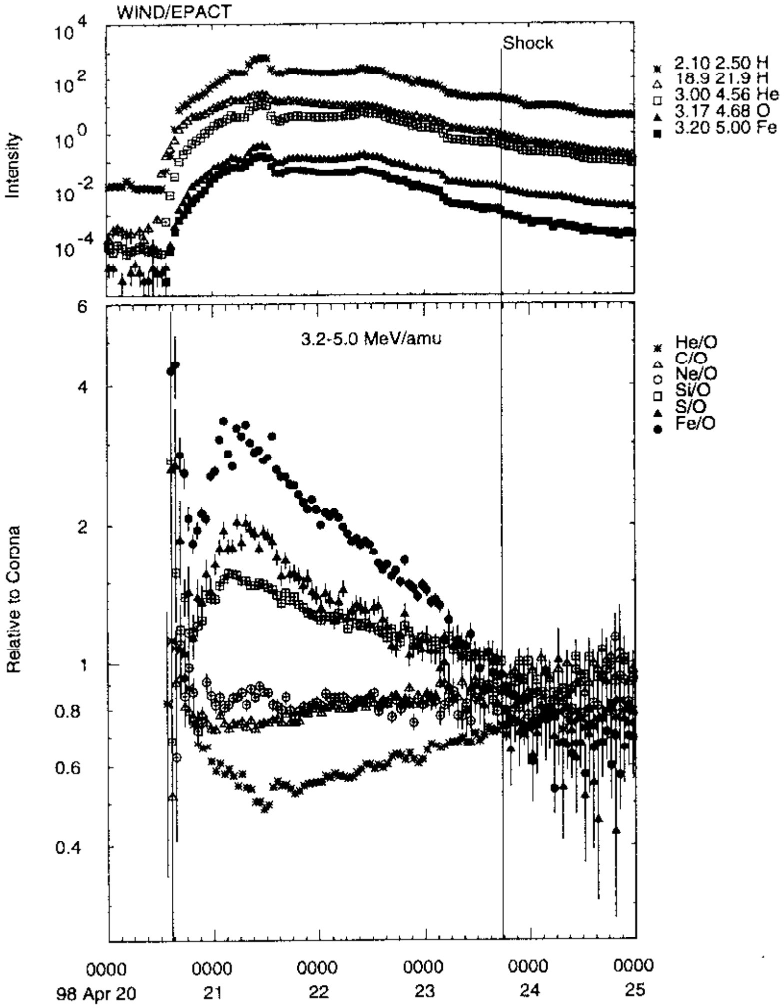

Fig. 6. Intensities of the listed species during the 1998 April SEP event observed on the Wind spacecraft are shown in the upper panel. The lower panel shows a spectacular systematic evolution in abundance ratios during the event.

point of magnetic connection moves along the face of the shock of varying strength and with differing wave intensities.

The energy dependence of abundances is a significant factor that we have not yet considered explicitly. Mazur *et al.* (1992) found that abundances were more likely to approach coronal values with smaller event-to-event fluctuations at the lowest energies, ~1 MeV/amu. At high energies, >10 MeV/amu, the effects of acceleration became more pronounced and event-to-event variations became much larger (see also Tylka, Dietrich, and Boberg 1997). With this in mind, we have focused on the lowest energies where adequate element resolution exists.

Having spent so much time discussing abundance variations, one might get the impression that the SEP abundances are not stable at all. However, for most elements with similar values of *Q/A*, SEP abundances are quite well determined. Event-averaged abundances of 5-12 MeV/amu Mg/Ne, normalized to the photospheric ratio, are shown in Figure 7 as a function of time spanning 7 years. The standard deviation of a single event from the mean is less than 20% for these events and the error in the mean itself is only ~3%. Mg/Ne is a principal determinant of the amplitude of the FIP effect.

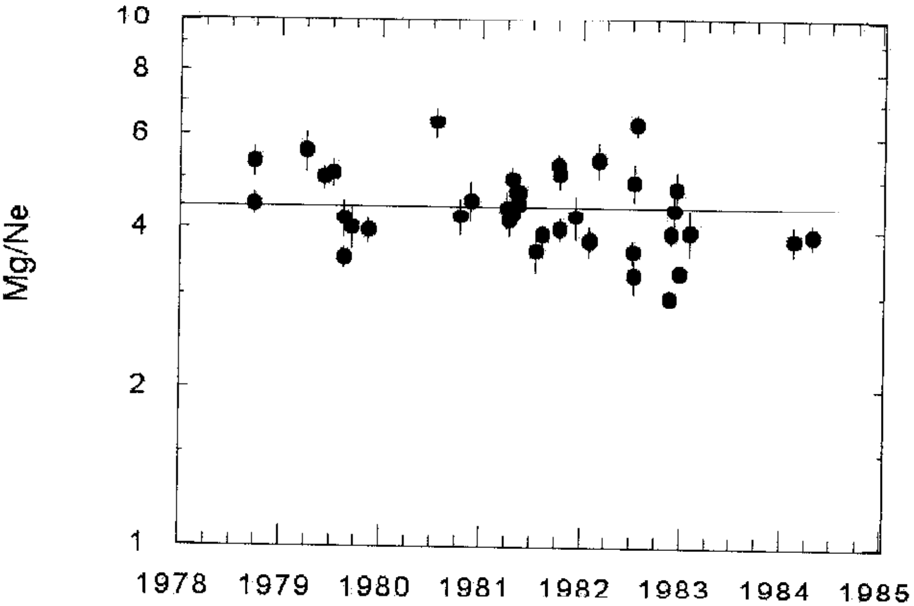

Fig. 7. Mg/Ne, relative to the corresponding photospheric ratio (Table 1), in gradual SEP events spanning 7 years.

3. Impulsive Solar-Flare Events

Energetic particles from impulsive flare events would not seem to be a good source of information on coronal abundances. Electromagnetic ion cyclotron

(EMIC) waves are produced between the gyrofrequencies of H and ^{4}He by streaming electrons in the flare plasma (Temerin and Roth 1992). The rare isotope ^{3}He, the only species whose gyro-frequency lies in this region, resonantly absorbs the waves, resulting in 1000-fold enhancements in ^{3}He/^{4}He ratios in the accelerated particles. Waves below the gyro-frequency of ^{4}He lead to enhancements in heavy elements (*e.g.* Miller and Reames 1996). Ne/O, Mg/O, and Si/O are enhanced by a factor of about 3 and Fe/O by a factor of about 7, relative to *coronal* abundances (Reames, Meyer, and von Rosenvinge, 1994; Reames 1995a).

Ionization state measurements of the energetic particles from impulsive events (Luhn *et al.* 1987) show the charge state of Fe to be 20.5±1.2 while Si and all elements below it are fully ionized. These charge states are appropriate to heating of the ions to a temperature ~10 MK in the flare. However, if the fully ionized ions have the same value of Q/A and resonate with the same waves, how can the enhancements in Ne/O, Mg/O, and Si/O occur? Reames, Meyer, and von Rosenvinge (1994) suggested that the heating and ionization occurs *after* acceleration. They interpreted the pattern of enhancements as evidence of acceleration of the ions from coronal plasma at a temperature 3-5 MK. At that temperature, the electron configurations of Ne, Mg, and Si are He-like and the three elements have similar values of *Q/A*, as shown in Figure 8, hence they are accelerated similarly. At that temperature, He and C are both fully ionized, so we expect He/C to have a value similar to that in the coronal source plasma. Thus, impulsive events confirm the SEP abundances for He/C, Mg/Ne and Si/Ne.

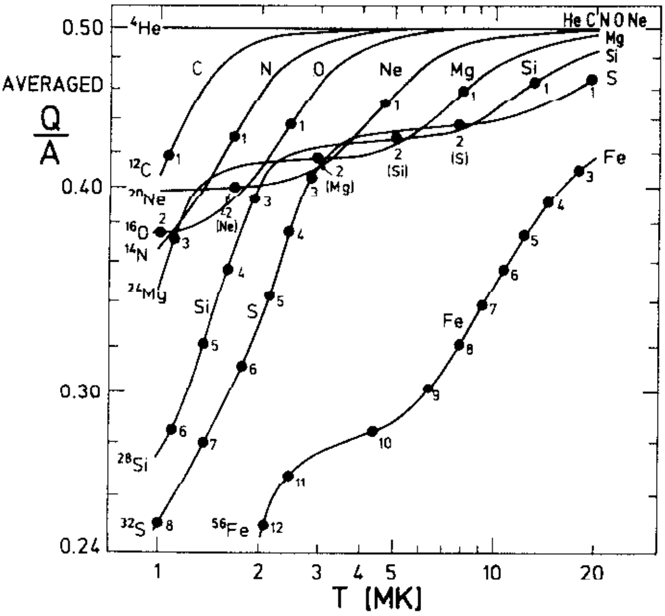

Fig. 8. Average Q/A as a function of plasma electron temperature based on Arnaud and Rothenflug (1985) and Arnaud and Raymond (1992) as plotted by Reames, Meyer, and von Rosenvinge (1994).

When averaged over many flares, the abundance enhancements show a pronounced dependence on *Q/A* when *Q* is taken as the value at ~3 MK as shown in Figure 9 (Reames 1995a). However, individual impulsive events do not show a systematic *Q/A* dependence as they do in gradual SEP events, although the statistics are not as good (Reames, Meyer, and von Rosenvinge 1994).

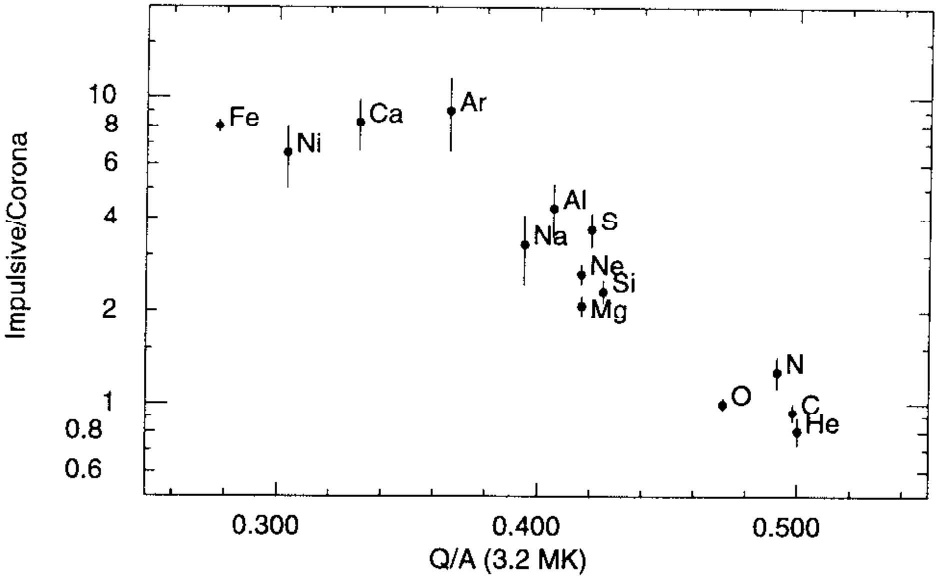

Fig. 9. The average abundance enhancement in impulsive-flare events *vs.* *Q/A* at 3.2 MK.

Finally, it is important to mention abundances obtained from γ-ray line measurements in solar flares. These measurements have now been made in several events and they also show the FIP-effect of coronal abundances (*e.g.* Ramaty, Mandzhavidze, and Kozlovsky 1996).

4. Co-rotating Interaction Regions

Co-rotating interaction regions (CIRs) are formed when high-speed solar-wind streams are emitted behind low-speed solar wind because of solar rotation. From the interaction a forward shock wave propagates outward into the low-speed wind and a reverse shock propagates sunward into the high-speed stream. Generally the shocks form outside 1 AU and strengthen out to several AU. While ions are accelerated at both shocks, those accelerated from the high-speed stream at the reverse shock predominate and are often observed streaming sunward at 1 AU.

The FIP dependence of these accelerated ions was first shown by Reames, Richardson, and Barbier (1991). Their FIP effect is similar to that seen in the fast solar wind itself (Gloeckler and Geiss 1989). Here the low-FIP elements are enhanced by a factor of only ~2 relative to the high-FIP elements, rather than the factor of ~4 we see in SEP events and in the low-speed wind. The presence of interstellar pickup ions in the solar wind also affects the abundances of H and He in the accelerated particles (Gloeckler *et al.*, 1993; Reames 1995).

Another interesting feature of energetic ions from CIRs is that a high value of C/O = 0.89±0.04 makes C move up to the level with the low-FIP ions. This is to be contrasted with a value of ~0.7 in the solar wind and 0.47±0.01 in the corona or photosphere. Richardson *et al.* (1993) found that the C/O ratio of the energetic ions was a function of the solar wind speed. This finding has been confirmed recently by Mason *et al.* (1997) using the high-resolution data from the Wind spacecraft. These results are shown in Figure 10.

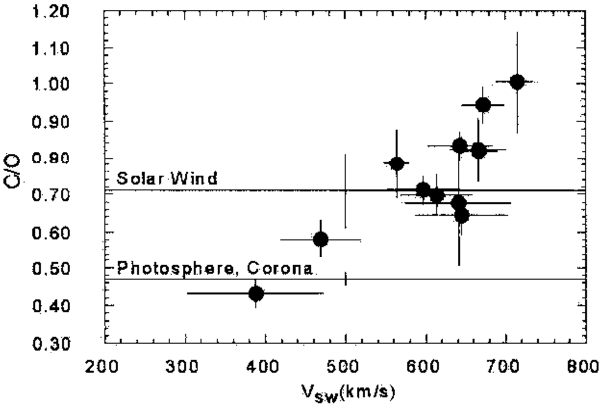

Fig. 10. C/O ratio of energetic ions from CIR events *vs.* the speed of high-speed stream.

5. Prospects

Energetic particles already provide information on the coronal abundances of a large number of elements. New observations on the Wind, SOHO, and ACE spacecraft can be expected to extend these measurements to heavier elements, to rarer elements and to isotopes.

Our greatest challenge now is to understand the physics of particle acceleration, both for its own sake and to improve our knowledge of the underlying source abundances. New measurements of abundance variations with improved statistics and higher time resolution may prove to be of great assistance here as well.

I would like to thank ISSI for their hospitality during this workshop and to thank C. K. Ng, A. J. Tylka , and T. T. von Rosenvinge for their comments on this manuscript. I also thank an unnamed referee for some helpful comments.

References

Arnaud, M., and Raymond, J.: 1992, *Astrophys. J.* **398**, 394.
Arnaud, M., and Rothenflug, R.: 1985, *Astron. and Astrophys. Suppl.* **60**, 425.
Bertsch, D.L., Fichtel, C.E., and Reames, D. V.:1969, *Astrophys. J. (Letters)*, **157**, L53.
Boberg, P. R., Tylka, A. J., and Adams, J. H.: 1996, *Astrophys. J. (Letters)* **471**, L65.
Breneman, H. H., and Stone, E. C.: 1985, *Astrophys. J. (Letters)*, **299**, L57.

Cliver, E. W.: 1996, in *High Energy Solar Physics*, edited by R. Ramaty, N, Mandzhavidze and X.-M. Hua, , AIP Conf. Proc **374**, (Woodbury, NY: AIP press), p. 45.

Fichtel, C. E., and Guss, D. E.: 1961, *Phys. Rev. Lett.* **6**, 495.

Garrard, T. L., and Stone, E. C.: 1994, *Adv. Space Res.* **14** (No. 10), 589.

Gloeckler, G., *et al.*: 1993, *Science* **261**, 70.

Gloeckler, G., and Geiss, J.: 1989, in *Cosmic Abundances of Matter*, edited by C. J. Waddington, A I. P. Conf. Proc. **183**, (NY: AIP press) p.49.

Gosling, J. T.: 1993., *J. Geophys. Res.* **98**, 18949.

Grevesse, N., Noels, A., and Sauval, A. J.: 1996, in *Cosmic Abundances*, edited by S. Holt and G Sonneborn, A. S. P. Conf. Series **99**, p. 117.

Kahler, S. W.: 1992, *Ann. Rev. Astron. Astrophys.* **30**, 113.

Kahler, S. W.: 1994, *Astrophys. J.* **428**, 837.

Lee, M. A.: 1983, *J. Geophys. Res.* **88**, 6109.

Luhn, A., *et al.*: 1985, *Proc. 19th Internat. Cosmic-Ray Conf.*, (La Jolla) **4**, 241.

Luhn, A., Klecker, B., Hovestadt, D., and Möbius, E.:1987, *Astrophys. J.* **317**, 951.

Marsch, E., von Steiger, R., and Bochsler, P.: 1995, *Astron. Astrophys.* **301**, 261.

Mason, G. M., Gloeckler, G., and Hovestadt, D. 1984, *Astrophys. J.* **280**, 902.

Mason, G. M., Mazur, J. E., Dwyer, J. R., Reames, D. V., and von Rosenvinge, T. T.: 1997, *Astrophys. J. Letters*, **486**, L149.

Mazur, J.E., Mason, G.M., Klecker, B., and McGuire, R.E.: 1992, *Astrophys. J.* **401**, 398.

Meyer, J. P.: 1985, *Astrophys. J. Suppl.* **57**, 151.

Meyer, J. P.: 1993, in *Origin and Evolution of the Elements*, edited by N Prantzos, E. Vangioni-Flam and M. Casse (Cambridge Univ. Press), p. 26.

Meyer, J. P.: 1996, in *Cosmic Abundances*, edited by S. Holt and G. Sonneborn, A. S. P. Conf. Series **99**, p. 127.

Miller, J. A., and Reames, D. V.: 1996, in *High Energy Solar Physics*, edited by R. Ramaty, N Mandzhavidze, X.-M. Hua, AIP Conf. Proc. **374**, (Woodbury, NY: AIP press), p. 450.

Ramaty, R., Mandzhavidze, N. and Kozlovsky, B.: 1996, in *High Energy Solar Physics*, edited by R Ramaty, N, Mandzhavidze and X.-M. Hua, , AIP Conf. Proc **374**, (Woodbury, NY: AIP press) p. 172.

Reames, D. V.: 1990, *Astrophys. J. Suppl.* **73**, 235.

Reames, D. V.: 1993, *Adv. Space Res.* **13** (No. 9), 331.

Reames, D. V.: 1995a, *Adv. Space Res.* **15** (No. 7), 41.

Reames, D. V.: 1995b, *Revs. Geophys. (Suppl.)* **33**, (U. S. National Report to the IUGG), 585.

Reames, D. V.: 1997, in: *Coronal Mass Ejections*, edited by N. Crooker, J. A. Jocelyn, J. Feynman Geophys. Monograph **99**, (AGU press) p. 217.

Reames, D. V., Meyer, J. P., and von Rosenvinge, T. T.: 1994, *Astrophys. J. Suppl.*, **90**, 649.

Reames, D.V., Richardson, I.G., and Barbier, L.M.: 1991, *Astrophys. J. (Letters)* **382**, L43.

Richardson, I.G., Barbier, L.M., Reames, D.V., and von Rosenvinge, T.T.: 1993, *J. Geophys. Res.* **98**, 13.

Temerin, M. and Roth, I.: 1992, *Astrophys. J. (Letters)* **391**, L105.

Tylka, A. J., Dietrich, W. F., and Boberg, P. R.: 1997, *Proc. 25th Internat. Cosmic-Ray Conf.*, (Durban) **1**, 101.

Tylka, A. J., Reames, D. V., and Ng, C. K.: 1998, in preparation.