Mean Element Abundances in Energetic Particles from Impulsive Solar Flares

Donald V. Reames
NASA/ Goddard Space Flight Center, Greenbelt MD, USA

ABSTRACT

The mean abundances of elements is determined in the 4 - 12 MeV/amu particles from 139 impulsive solar-flare events and from 18 large gradual events (coronal abundances). The element enhancements in the impulsive events are organized as a function of Q/A of the ions at a plasma temperature of ~3 MK that is typical of that in solar active regions. Ions are accelerated by waves produced by streaming electrons and are subsequently ionized further by electrons from the same beam.

1. INTRODUCTION

The abundances of energetic ions from impulsive solar flares are characterized by enhancements in $^3He/^4He$ by 3-4 orders of magnitude and in heavy elements, *e.g.* Fe/O, by an order of magnitude, relative to the corresponding abundances in the solar corona or solar wind (see Reames 1990 and references therein). It is likely that these enhancements occur as the particles are accelerated by resonant interactions with plasma waves produced by intense beams of ~10 keV electrons that always accompany the ions in these events (Temerin & Roth 1992; Miller & Viñas 1993). The magnitude of the enhancements in ^3He is uncorrelated with that in the heavy ions, presumably because ^3He, with Q/A=0.667 resonates with H^+ electromagnetic-ion-cyclotron waves while the heavy ions, with Q/A<0.5, resonate with shear Alfvén waves.

In a recent study (Reames, Meyer & von Rosenvinge, 1993), we examined the flare-to-flare variations in the abundances of H, ^3He, ^4He, C, N, O, Ne, Mg, Si, S and Fe for a sample of 139 impulsive flares. Generally speaking, both the enhancements and their variations are much more modest for the elements with Z>2 than for ^3He. The element abundances seem to be organized into three groups, ^4He-O, Ne-Si, and Fe with factor of ~3 enhancements between consecutive groups. This grouping of the abundances was interpreted in terms of the temperature of the preflare gas of ~3.5 MK, where the elements up to O are essentially fully ionized, with Q/A=0.5, those in the Ne-Si group are He-like, with Q/A~0.42, and Fe has a charge of ~+16 so that Q/A~0.26. Only in the region near 2-4 MK do the elements Ne, Mg and Si have similar values of Q/A so they all resonate with the same waves and are similarly enhanced. The ions are further ionized by the electron beam on the same time scale (~10 s) as their acceleration (Miller & Viñas 1993; Reames, Meyer & von Rosenvinge 1993).

In this paper we extend the abundance observations to include the rarer elements Na, Al, Ar, Ca, Cr, Ni and Zn. Since these elements are not sufficiently abundant to study in individual solar events, we have accumulated the observations during all of the impulsive event periods. For comparison with coronal abundances we have made a similar accumulation during 18 large gradual events that occurred between 1980 Sept. 1 and 1982 Sept. 1. The large gradual events are produced by shock acceleration of ions from the corona and solar wind, and it has been shown (see reviews by Reames 1992; Meyer 1993) that averages over many of these events give abundances that reflect those of the solar corona.

2. OBSERVATIONS

The observations reported in this paper were made over a 12-year period by the Goddard instrument aboard the *ISEE 3* spacecraft. The observations of the very-low-energy telescope (VLET) and the properties of the impulsive flare periods are fully described by Reames, Meyer and von Rosenvinge (1993). The VLET consists of two 15 micron thick surface barrier detectors, D_1 and D_2, followed by a 300 micron detector, E, and an anticoincidence detector. For ions that stop in the E detector, energy losses in the three detectors, D_1, D_2 and E, over-determine the atomic number, Z, and energy of the ion. Our primary estimate of Z is taken from D_1+D_2 *vs.* E, and a second estimate, Z_2, is made from D_2 *vs.* E. Figure 1 shows the percentage difference between the two estimates as a function of Z for all of the particles from the impulsive events.

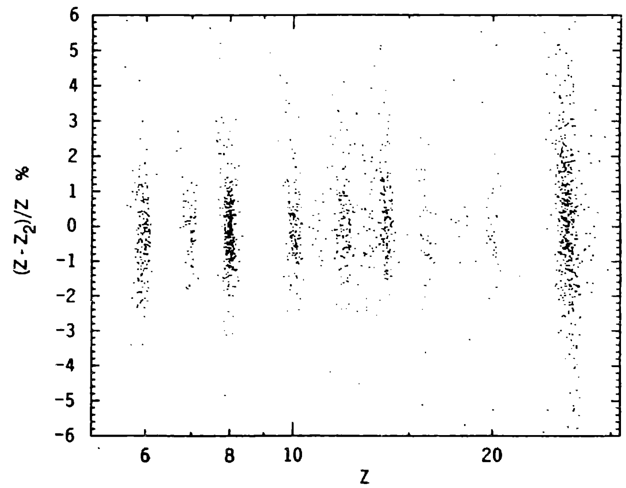

Fig. 1. Percentage difference in estimates of Z *vs.* log Z

The particles with best estimates of Z are in the region of Figure 1 where $(Z-Z_2)/Z$ is near 0. Figure 2 shows a histogram of abundance *vs.* Z for those particles that have $|(Z-Z_2)/Z| < 1.5\%$. The abundances in Figure 2 will have a bias that slowly increases with Z since the width of the distribution is larger at Fe than at C. However, if we use the full distribution to determine the abundances of the dominant elements and use the selected distribution to find ratios such as Na/NeMg or Al/MgSi, no bias will result.

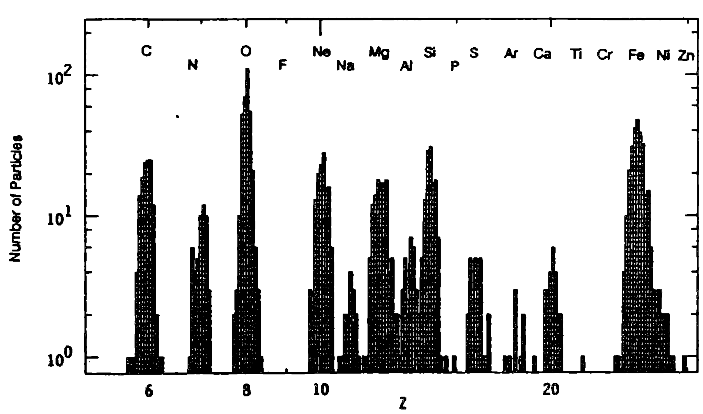

Fig. 2. Histogram of abundance *vs.* log Z in impulsive events.

Abundances were analyzed in exactly the same way for the large gradual events. The number of particles with Z≥6 was 1720 for the impulsive events and 53855 for the gradual events. The element abundances are shown for both populations in Table 1.

3. RESULTS AND DISCUSSION

The abundance enhancements, obtained as the ratio of abundances in impulsive and gradual events, is shown as a function of Z in Figure 3a. Note that Na and Al are well above their neighbors in this plot, and Ar and Ca have enhancements similar to that of Fe. Following the analysis of Reames, Meyer and von Rosenvinge (1993), the enhancements are plotted as a function of Q/A at a temperature, T, of 3.2 MK in Figure 3b. The charge states, Q, are taken from Arnaud and Raymond (1993) for Fe and from Arnaud and Rothenflug (1985) for the other elements plotted. Note the clustering of ^{4}He, C, N and O at Q/A~0.5 (more pronounced at higher T) and Ne, Mg, Si and S at Q/A~0.42. Particles with the same Q/A should interact with the same waves and receive the same enhancement.

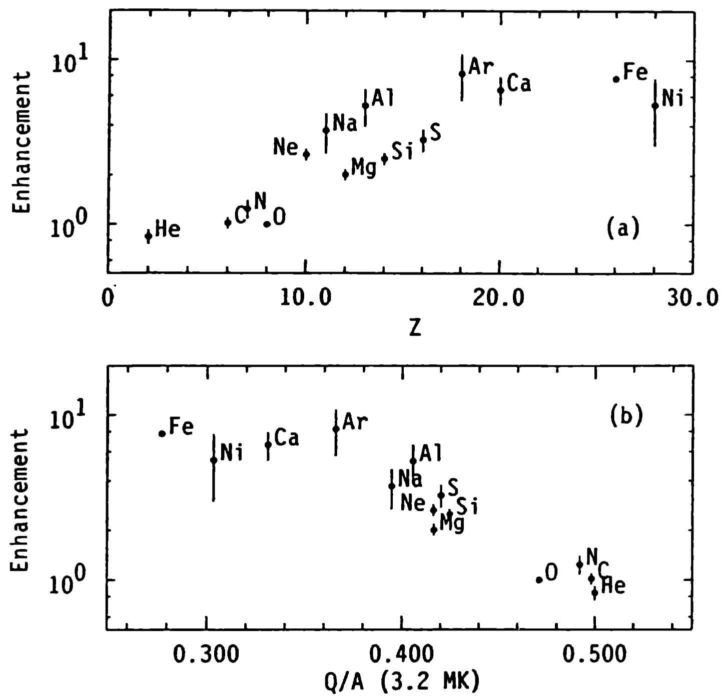

Fig. 3 Element enhancements *vs.* (a) Z and (b) Q/A at 3.2 MK.

Generally speaking, the enhancements of the elements Na, Al, Ar, Ca and Ni are consistent with the pattern established by the more abundant species. At the typical temperature chosen, they all lie at 0.3 < Q/A < 0.41, between the Q/A values of Fe and NeMgSi, and there enhancements are also between those of those two groups. Most of the discrepancies from a smooth Q/A dependence have been discussed previously (Reames, Meyer & von Rosenvinge 1993). These include differences in the abundances of He, C, N and O, which lie in a region where all waves may be absorbed by ^{4}He. The statistically large enhancements Ne and S relative to Mg and Si are also puzzling and may come from enhancements in the pre-flare gas.

Of course, it is unlikely that all flares begin in a plasma of the same temperature and, furthermore, the enhancement at the mean Q/A is not the same as the mean enhancement for a distribution of discrete values of Q. At present, however, Figure 3b provides our only estimate of the wave spectrum seen by the ions below the ^{4}He gyrofrequency. While it is possible to estimate the growth rate of waves in this region (Miller & Viñas 1993), determination of the saturation of the waves and the resulting wave energy spectrum is much more difficult.

Finally, the abundances in gradual events shown in Table 1 represent a new determination of coronal abundances. Recent X-ray measurements (McKenzie & Feldman 1993) suggest higher abundances of elements at low first-ionization-potential (FIP), Cr, Ca and Al, than those reported by Breneman & Stone (1985, B&S). Our abundances of Na, Al and Ca are all about 10% higher than those of B&S, but they are not in statistical disagreement. Please note that the *observed* abundances of B&S should be used as coronal abundances rather than their "SEP-deduced corona" since the latter were deduced based on an erroneous photospheric abundance for Fe (see Reames 1992; Meyer 1993).

TABLE 1.

ABUNDANCES IN IMPULSIVE AND GRADUAL EVENTS

	Impulsive	Gradual (Corona)
Normalized to O:		
^{4}He	46000 ±4000	55000 ±3000
C	436 ± 34	426 ± 10
N	153 ± 20	123 ± 3
O	1000 ± 51	1000 ± 9
Ne	416 ± 33	156 ± 5
Na	51 ± 13	13.7 ± 1.4
Mg	413 ± 33	204 ± 4
Al	88 ± 17	16.6 ± 2.8
Si	405 ± 33	161 ± 4
P	3 ± 3	0.3 ± 0.15
S	121 ± 18	37 ± 2
Cl	< 3	0.3 ± 0.3
Ar	29 ± 9	3.5 ± 0.2
Ca	79 ± 14	11.9 ± 1
Ti	< 5	0.8 ± 0.3
Cr	9 ± 6	2.0 ± 0.6
Fe	1234 ± 57	159 ± 3
Ni	36 ± 14	6.7 ± 1.4
Zn	5 ± 5	0.13± 0.10

I would especially like to thank J. P. Meyer and J. A. Miller for many helpful discussions.

REFERENCES

Arnaud, M., & Raymond, J. 1992, ApJ 398, 394.
Arnaud, M., & Rothenflug, R. 1985, A&A Suppl. 60, 425.
Breneman,H. & Stone,E.C. 1985, ApJ (Letters), 299, L57.
McKenzie, D.L., & Feldman, U. 1993, ApJ submitted.
Meyer, J.P., 1993, In: Origin and Evolution of the Elements, eds. N. Prantzos, E. Vangioni-Flam & M. Cassé (Cambridge Univ. Press) in press.
Miller, J.A. & Viñas, A.F. 1993 ApJ, in press (July 20).
Reames,D.V. 1990, ApJ Suppl. 73, 235.
Reames,D.V. 1992, In: Coronal Streamers, Coronal Loops, and Coronal and Solar Wind Composition, (1st SOHO Workshop, Annapolis) ed. V. Domingo, ESA SP-348, p 315.
Reames,D.V., Meyer,J.P., & von Rosenvinge,T.T. 1993, ApJ Suppl., submitted.
Temerin, M. & Roth, I. 1992, ApJ (Letters) 391, L105.