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TEMPERATURE DEPENDENCE OF THE ABUNDANCES OF ELEMENTS IN SOLAR ^{3}He-RICH EVENTS

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ABSTRACT

The element abundances in solar ^{3}He-rich events are observed to vary with the soft X-ray temperature of the parent flare. The observations are consistent with thermal collisional ionization of the elements to the equilibrium-charge states expected within the flare-heated plasma at (10–15) $\times 10^6$ K. Proposed photoionization mechanisms appear to be excluded. Rapid ionization of the ions requires that the heating occur sufficiently low in the corona that the electron density exceed about (1–5) $\times 10^8$ cm^{-3}. Heavy-element enhancements might be a signature of material processed in the flash phase of events in contrast to unheated ambient material accelerated by a coronal shock.

Subject headings: Sun: abundances — Sun: corona — Sun: flares

I. INTRODUCTION

Solar ^{3}He-rich events are known to have enhancements in heavy elements that can be nearly as dramatic as the enhancement in the ^{3}He/^{4}He ratio itself (see reviews by Ramaty *et al.* 1980; Kocharov and Kocharov 1984; Lin 1987; and Mason 1987). A surprising new result found by Mason *et al.* (1986), however, is that the event-to-event variations in ^{3}He and in heavy elements are uncorrelated. Those authors were unable to reconcile this behavior with the Fisk (1978) model, for example, that relates the enhancements of ^{3}He and heavy elements.

Meanwhile, it has been possible to identify a significant number of flares in which these particles are accelerated (Reames, von Rosenvinge, and Lin 1985; Reames and Stone 1986). Recently Reames *et al.* (1988) studied the X-ray and radio properties of these events and found the ^{3}He/^{4}He ratio to be anticorrelated with measures of the X-ray or radio intensity, but uncorrelated with the soft X-ray temperature. This sample of identified events is more suitable for the study of variations in composition than sample used by Mason *et al.* (1986), since the latter included time periods containing multiple unresolved events.

The enhancements of heavy nuclei are likely to depend, in some way, upon their charge states. Klecker *et al.* (1984) deduced that these charge states were anomalously high in ^{3}He-rich events as a result of higher temperatures in the flares. In this context it seemed appropriate to investigate the temperature dependence of the enhancements directly, using the recently measured soft X-ray temperatures. Separately, Mullen and Waldron (1986) have suggested that the heavy elements are photoionized in large flares so that their ionic charge states might be expected to depend upon the X-ray emission measure, a hypothesis that may also be tested in these events.

II. OBSERVATIONS

All of the observations reported here were made on the *ISEE 3* spacecraft in orbit about the Sun-ward libration point. Element abundances were measured in the same Very Low Energy Telescopes (VLETs) as the He isotopes that were used for the identification of all of the ^{3}He-rich events discussed above (see Reames, von Rosenvinge, and Lin 1985). Soft X-ray measurements were made with the Berkeley X-ray Spectrometer (Anderson *et al.* 1978); however, all of the X-ray temperatures and emission measures used here were taken directly from Table 1 of Reames *et al.* (1988) and are described therein. The temperatures usually correspond to the time of hard X-ray maximum.

Abundances of elements, relative to ^{4}He, are shown as a function of the soft X-ray temperature in Figure 1. All species are measured in a 2–3 MeV/AMU energy interval. The same reference abundances used by Mason *et al.* (1986) to define enhancements are shown as a dashed line in the figure. These reference abundances were obtained by Mason *et al.* (1980) by averaging the low-energy element abundances in many large flares. It should be noted that these reference abundances already exhibit significant heavy-element enhancement when compared to photospheric abundances.

Correlation coefficients corresponding to each of the plots in Figure 1 are shown in Table 1. The element abundance enhancements show a statistically meaningful increase with temperature in several cases.

None of the element enhancements show any statistically significant correlation with the X-ray emission measure or peak flux; however, Figure 2 shows the Fe/^{4}He ratio versus emission measure as an example.

As noted by Reames *et al.* (1988), the presence of multiple X-ray peaks in several of the events cause uncertainty in the value of the characteristic temperature of the events. This uncertainty undoubtedly contributes to the scatter of the points in Figure 1.

III. RESULTS AND DISCUSSION

Several of the elements shown in Figure 1, especially Mg, Si, S, and Fe, show enhancements that increase with the soft X-ray temperature; none show any correlation with the X-ray emission measure or other parameters related to the X-ray intensity of the event. This behavior differs markedly from that of ^{3}He which is inversely correlated with emission but uncorrelated with temperature (Reames *et al.* 1988). From this perspective it is not surprising that Mason *et al.* (1986) were unable to correlate the enhancements in heavy ions with those in ^{3}He.

The existence of a correlation between the ion abundances and the X-ray temperature suggests that the ions are indeed

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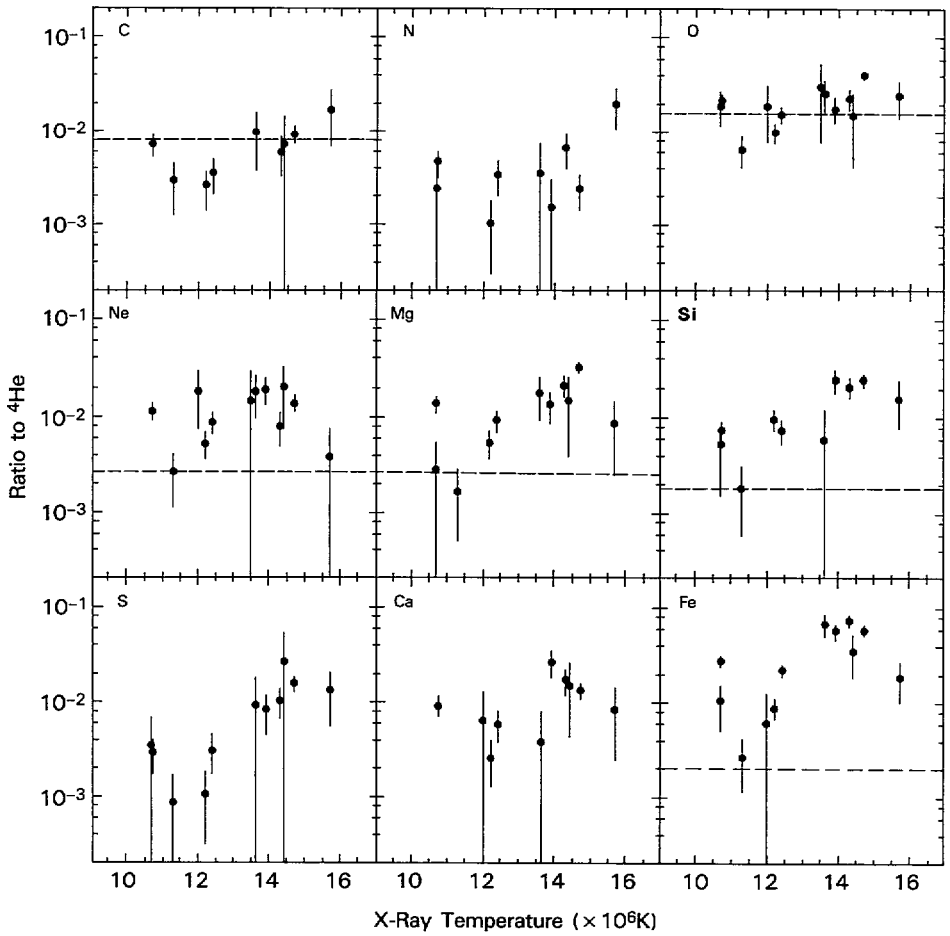

FIG. 1.—Abundances of elements in ^{3}He-rich events as a function of the soft X-ray temperature. Each panel shows the ratio of the abundance of the indicated element to that of ^{4}He in the 2.0–3.1 MeV/AMU interval. Dashed lines indicate the reference abundances in large flares (Mason *et al.* 1980).

accelerated at the time that the temperature measurement was made, i.e., at the time of hard X-ray maximum.

It is most likely that the temperature dependences seen above result from changes in the ionization states of the various species. The Fisk (1978) mechanism (see also Varvoglis and Papadopoulis 1983) produces a resonance heating of ions when the second harmonic of their cyclotron frequency lies near the frequency of the unstable waves. Fisk identifies $^{12}C^{+4}$, $^{16}O^{+5}$, and $^{56}Fe^{+17}$, for example, as meeting this criterion. In the range of temperatures shown in Figure 1, however, C and O would be completely stripped and equilibrium charge state of Fe would be in the range 19–24 according to the collisional ionization models (Jordan 1969; Shull and Van Steenburg 1982).

Klecker *et al.* (1984) have reported a mean charge of 19 ± 2

TABLE 1

TEMPERATURE CORRELATION OF THE ELEMENT ABUNDANCES

Species	Coefficient	Events	Probability
C	0.694	9	96%
N	0.448	9	...
O	0.483	13	91
Ne	0.154	12	...
Mg	0.629	11	96
Si	0.734	10	98
S	0.803	11	99
Ca	0.427	10	...
Fe	0.611	12	96

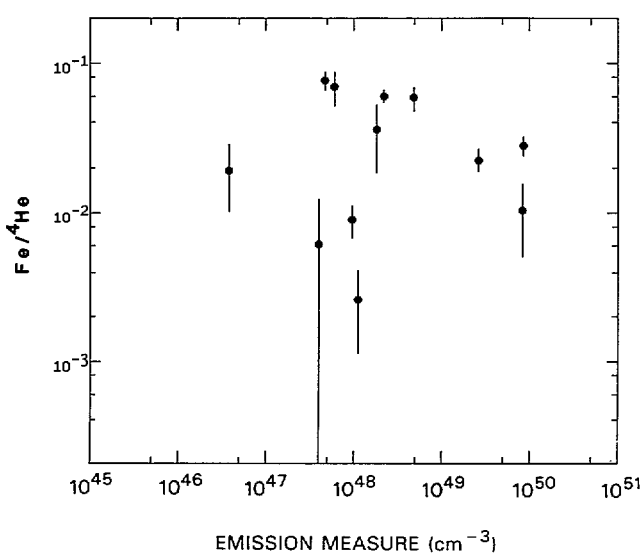

FIG. 2.—The Fe/^{4}He ratio as a function of soft X-ray emission measure showing no evidence of correlation.

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for Fe ions in ^{3}He-rich events. This value was obtained by accumulating ions during several ^{3}He-rich periods and would therefore be biased in favor of the high-temperature events with larger Fe enhancements. Luhn *et al.* (1985) extended these measurements to a larger sample of events and found a mean charge of Fe of 20.6 ± 1.2; they also found that Si was consistent with being fully stripped.

These measured charge states are higher than those expected for the Fisk mechanism, although they agree well with the charge states inferred from the X-ray temperatures in these events assuming the charge states to be in thermal equilibrium (Shull and Van Steenberg 1982). Apparent agreement between the measured and inferred charge states raises a new problem, however. If elements like Mg and Si are fully stripped in these events, what is the origin of the temperature dependence for these species as seen in Figure 1?

One might expect that the X-ray emitting region is surrounded by a region through which the temperature decreases until it reaches the level of the ambient corona. Depending upon the geometry of the acceleration region, substantial volumes of material could be ionized to the proper charge state for resonant acceleration of the heavier ions even though the temperature of the central heated region rose to excessively high values.

The temperature dependence of the element enhancements strongly suggests that the ions are thermally ionized. The observations appear to rule out photoionization mechanisms, such as that suggested by Mullen and Waldron (1986), for the ^{3}He-rich events. Mechanisms based upon X-ray photoionization should correlate with the X-ray emission measure, i.e., with the number of ionizing photons available, rather than the temperature. As stated previously, *none* of the element abundances show any significant correlation with either soft X-ray emission measure or the soft X-ray peak flux near 5 keV.

If elements attain a new equilibrium charge state by collisional ionization during a flare and if the soft X-ray temperatures describe the electron-temperature profile of the heating, then the observed soft X-ray time profiles (Reames *et al.* 1988) may be used to place limits on the time scale of the ionization process. If the heating occurs in a time of the order of 1–5 minutes as the time profiles suggest, then the process must occur in a region of the corona where the electron density is sufficiently high to provide enough ionizing collisions. Using the rates given by Shull and Van Steenberg (1982), one finds that a density of over $(1\text{–}5) \times 10^8$ electrons cm^{-3} is required to ionize Fe of charge $+20$ at a temperature of 10^7 K in the required time. This places an upper limit on the coronal height of the ionization region of 10^4–10^5 km. This is slightly below the lower limit of 1.5×10^5 km for the acceleration region as deduced from the low-energy end of the electron spectrum by Kahler *et al.* (1987).

Lin (1987) has suggested that particles accelerated in the impulsive, ^{3}He-rich events are derived from material heated within the flare itself, while the particles found in the large solar particle events are shock accelerated from the cooler ambient coronal material. This *Letter* strongly supports such an origin for the elements observed in the ^{3}He-rich events.

If heavy-element enhancements are indeed the product of flash-phase heating, then their existence in larger, more complex events might serve as a signature of flash-phase material. Enhanced abundances frequently occur at low energies in large events where the high-energy abundances differ little from coronal abundances.

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