ANOMALOUS ABUNDANCES OF SOLAR ENERGETIC PARTICLES AND CORONAL GAS: COULOMB EFFECTS AND FIRST IONIZATION POTENTIAL (FIP) ORDERING

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ABSTRACT

We argue that FIP ordering of elemental abundances in solar energetic particles and in the corona can both be explained Coulomb effects.

1. Introduction. Solar energetic particles (SEP) and coronal gas have anomalous abundances relative to the photosphere (1). The anomalies are similar in both cases: this led Meyer (1) to conclude that SEP acceleration is not selective, but merely preserves the source abundances (in the corona). Here, we argue that SEP acceleration can be selective, because identical selectivity operates to determine the coronal abundances.

The abundance anomalies are ordered by first ionization potential (FIP). Meyer (1) claims that this requires source temperatures of T=8000 K. However, we find that FIP ordering occurs even if $T > 10^6$K.

2. Coulomb effects in SEP. SEP pre-acceleration in magnetic reconnection (e.g. in a solar flare) favors ions with low Coulomb losses (2) (hereafter ML). Pre-acceleration selects ions with charge $Z < R A^{0.5}$. (A is atomic weight, R is a critical number.) ML argued that in a hydrogen dominated corona, where coronal heating itself depends on reconnection, R should lie close to the proton value, R=1.0. Then the pre-acceleration time scale t_B would be marginally shorter than the proton Coulomb loss time t_p. With R=1, pre-acceleration of (e.g.) iron ions will favor ions with $Z \leq 7$. This selection of certain (low) charge states gives rise to abundance anomalies in SEP (see (2)).

ML discussed two cases of reconnection in a coronal magnetic loop. Case A had $t_B < t_p$ only at the top of the loop; case B had $t_B < t_p$ at all points in the loop. Abundance anomalies in Case A were found to be quite large in some cases: to agree with observations, the anomalies would require dilution with non-processed material. Meyer (1) criticizes Case A because different flares would apparently require rather similar dilution factors. However, Case B yields anomalies which are much closer to the observed values. Dilution is irrelevant in Case B. In this paper, we refer only to Case B.

ML predicted that Na/Si, Mg/Si, Ca/Fe, and Ni/Fe should be less in flares than in the photosphere by factors of 2-3. Meyer (1) claims that SEP data do not support these predictions. However, the observed ratios have a large scatter in different flares (see Fig. 3 in (1)). The scatter is such that the lower limit on the above ratios can be smaller than photospheric by factors of 2-3 (as Case B predicts) except for Na/Si. Thus, the Na/Si ratios might present a problem for Case B: perhaps the ionization equilibria of Na are incorrect. Apart from Na, however, the data can be reconciled with Case B predictions, contrary to the claim in (1) that the ML scenario disagrees with the data. (Meyer (1) did not discuss Case B of ML).

As an indication of how the ML scenario succeeds, both qualitatively and quantitatively, in reproducing the observed elemental anomalies in energetic particles, we show Case B predictions and data in Fig. 1, as a function of FIP. (Both cases are normalized to Si). Experimental points in Fig. 1 are taken mainly from (1), but in the case of elements which have not yet been detected in solar cosmic rays, we took data from (3) for the galactic cosmic rays. (Elemental anomalies are quite similar in solar and galactic cosmic rays (1).) As regards the ML predictions plotted in Fig. 1, we note that no specific values were predicted in Case B for H and He. The nature of the ML scenario (marginal heating of H) is such that the amount of hydrogen selected for pre-acceleration depends in detail on the extent to which the margin is exceeded. This is not known: however, a firm prediction is that, since H and He in the corona have identical values of Z^2/A, the abundances of both H and He (whatever they are) should be identical. To show this in Fig. 1, we join the H and He predictions by a horizontal dashed line. The vertical placing of this line cannot be determined at the present level of detail: we have chosen to plot it so as to overlap with the error bars of the data for H and He.

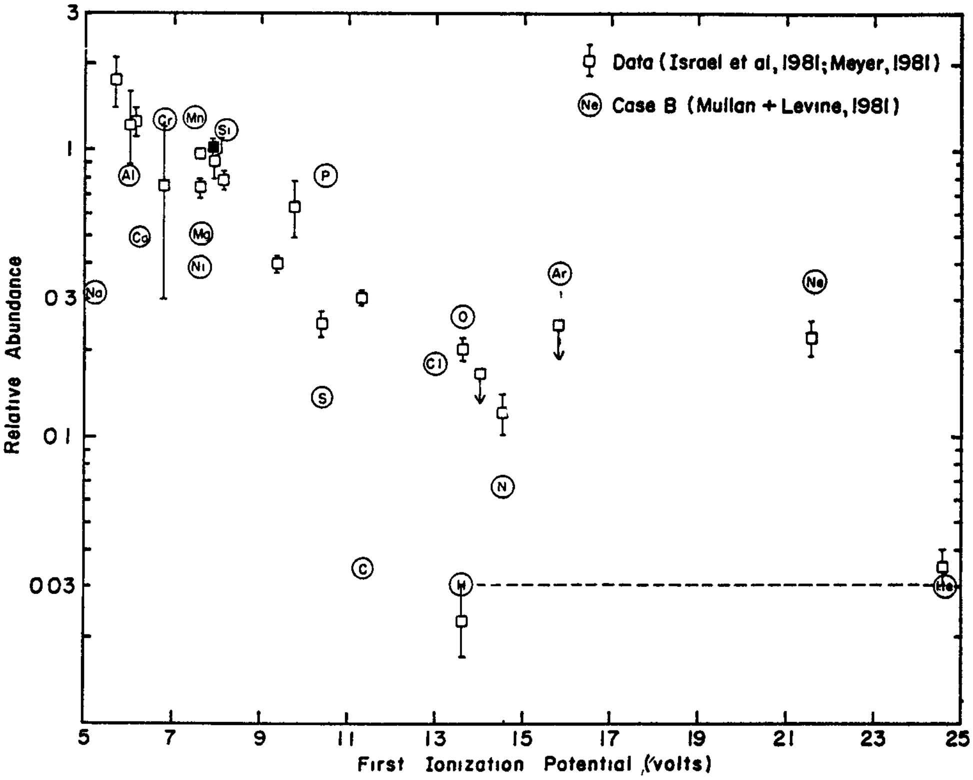

Fig. 1. Relative abundances of elements as a function of FIP.

The agreement between Case B predictions and data in Fig. 1 is quite good. Thus, both show maximum values of the abundance anomalies (around values of 1) at low FIP (except for Na), and both show a pronounced "step" down to lower values at about 10 volts. The lower abundances at large FIP are down for both by factors of 3-10 relative to those at low FIP. The "step" is well-defined in the Case B predictions: for the elements P, S, and C, the FIP values differ by < 10%, but their abundances differ by factors of ~ 1000%. The H and He data can be reconciled with the prediction of equal abundances: H need not be regarded as an exception in the Case B scenario. Note that the only free parameter in Case B is the loop thermal structure.

Since the ML predictions in Fig. 1 were obtained for coronal loops with $T \gg 10^6$K, an important conclusion from Fig. 1 is that FIP ordering of elemental abundances does not require a chromospheric phenomenon: it may occur even in the corona.

We stress that the predicted anomalies in Fig. 1 arise from a selection of ions with Z^2/A less than a critical ratio, viz. R=1.0. Abundance anomalies similar to those shown in Fig. 1 are expected to occur in any loop where ions with $Z < A^{0.5}$ are preferentially selected. This will be important to keep in mind when we consider the accumulation of minor ions in the solar corona due to solar wind outflow.

3. Solar Wind: Minor Ions. The solar wind consists mainly of protons, but minor ions are dragged along by Coulomb effects if the proton flux is sufficiently large. In order that ions of atomic weight A and charge Z be dragged out of the sun, the proton flux must exceed the minimum value

$$F_{min} = 3.4 \times 10^8 \, (T/10^6)^{3/2} \, G(A,Z) \, cm^{-2}s^{-1} \text{ (cgs).} \qquad [1]$$

Coronal temperature T will be taken to be 10^6 K here. G is a function of A, Z, and T (see (4)): in the limit of heavy ions, $G \simeq A/Z^2$.

The actual solar wind flux is not infinitely large: therefore, some ions will not be dragged out by the protons, but will instead be left behind to accumulate in the corona. Which ions are left behind? To answer this, we refer to the actual value of the solar wind flux. During the years 1962-1975, in low speed solar wind, the flux was 3.9×10^8 cgs on average; in high speed wind, it was 2.7×10^8 cgs on average; in a long term average, it was 3.8×10^8 cgs (5). As mentioned in (5), these fluxes are uncertain by factors of order 30%, and there is a rather large spread in the fluxes: the standard deviation in the long term average is 2.4×10^8 cgs (5). In a sample of solar wind recorded near solar maximum (August 1978 to February 1980) by ISEE-3, we have examined a series of 2117 "snapshots" of the solar wind, each lasting 3 seconds, with one "snapshot" every 5-6 hours throughout a 550-day interval. The mean flux we found was 3.2×10^8 cgs. This lies within the 30% uncertainty of the long term average in (5). It appears safe to adopt a mean solar wind flux of $(3\text{-}4) \times 10^8$ cgs.

The interesting aspect of these fluxes for our purposes can be seen from eq. [1]. The mean flux apparently suffices to drag out only those ions which have $G < (3\text{-}4)/3.4 = 0.9\text{-}1.2$, i.e. ions with $Z > (0.92\text{-}1.06)A^{0.5}$. The remaining ions, those with $Z \leqslant (0.92\text{-}1.06)A^{0.5}$, are left behind to enrich the corona.

There is no a priori reason why the solar wind flux should have any relationship whatever to the coefficient in eq. [1]. Thus, the mean value of the upper limit on the ratio $R = Z^2/A$ of the ions which would enrich the corona could be arbitrary, in principle. We draw attention to the fact that, in practice, however, the upper limit on R in the enriched coronal gas is equal to unity (within the uncertainties of the solar wind measurements). Thus, ions of (e.g.) iron with $Z \leq 7$ will accumulate in the solar corona.

4. Discussion. We have found that ions which are selectively preaccelerated in SEP (i.e. those with $R < 1$) are the same as those which enrich the coronal gas because the average solar wind leaves them behind. Therefore, abundance anomalies which appear in SEP because of the Coulomb selectivity are also expected to appear in the coronal gas. Thus, the predictions in Fig. 1 should also be relevant for abundances in the coronal gas, provided thermal structures are not too different. (Note that Case B predictions, which appear in Fig. 1, are insensitive to source temperature, as long as $T \geqslant 10^6$ K; see Fig. 8 of (2). Hence, differences in temperature between a solar flare site and the source region of the solar wind will not affect the predictions in Fig. 1, since both temperatures in all likelihood are $\geqslant 10^6$K.) We suggest that coronal abundances are anomalous relative to the photosphere because of Coulomb losses in the solar wind, while SEP anomalies are due to Coulomb losses at a flare site. Hence, SEP acceleration can be selective: but since it enhances the selection which has already occurred in the corona, the anomalies appear similar. Different classes of Fe-richness in SEP may reflect situations in the sun where SEP selectivity and/or solar wind selectivity have operated and reinforced each other to varying extents.

The enrichment of the solar corona will not proceed indefinitely: at times, the solar wind flux becomes considerably larger than average. Thus, in the data set discussed in (5), the 5-95% range limit on the solar wind flux is $(1.5-7.8) \times 10^8$ cgs. In 550 days of ISEE-3 data, we found 9 samples (out of 2117) with fluxes of $(9.0-9.9) \times 10^8$ cgs. each separated by an average interval of about 60 days. At such times, the accumulated enrichment of 60 days is flushed out, such that only ions with very small Z are left behind ($Z < (0.5-0.6)A^{0.5}$). But on the average, enrichments of coronal gas will build up with abundance anomalies as shown in Fig. 1.

5. Conclusions. Elemental abundances are observed to be anomalous (relative to the photosphere) in both SEP and in coronal gas. Here we propose that Coulomb effects can explain both sets of anomalies. The Coulomb loss scenario makes predictions of elemental anomalies as a function of FIP and these predictions agree well both qualitatively and quantitatively with the observed data for energetic particles (see Fig. 1). FIP ordering is not a sign that the source material is at T=8000 K: we find that the source material can have $T \geqslant 10^6$K, and still preserve FIP ordering.

References

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