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Heavy Ions in the October 1989 Solar Flares Observed on the Galileo Spacecraft

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ABSTRACT: Composition measurements were made of the energetic particles produced in the series of large flares which began on 19 October 1989, using the Galileo Heavy Ion Counter which is sensitive to nuclei ranging from carbon (Z=6) to nickel (Z=28) over an energy range from about 5 MeV/nucleon to >70 MeV/nucleon. The observations are unique in that clean, statistically well-measured abundances are available for heavy ions for an unusually large flare. For elements with low First Ionization Potential (FIP), these results show the same correlation of relative abundances with the ion charge to mass ratio as the earlier Voyager observations of solar energetic particles[1]. After correction for selection on the basis of this charge to mass ratio, the abundances of all the elements measured show the expected step-function correlation with FIP, when compared to the spectroscopic photspheric abundances.

INTRODUCTION: This work has the objective of studying the solar composition using the abundances of solar energetic particles (SEPs) and of testing the applicability of the techniques of Breneman and Stone[1] (hereafter B&S) to these unusually large flares. SEPs from large solar flares are generally agreed to reflect the abundance of the solar corona -- B&S showed good correlation between SEP abundances and spectroscopic coronal abundances, after a correction is made for a Q/M (ion charge to mass ratio) fractionation, presumably reflecting acceleration and transport processes.

Galileo was launched on 18 October 1989, and the Heavy Ion Counter (HIC) was turned on early on 21 October (DOY 294), while the SEP fluxes from the very large flare of 19 October were still high enough to allow acquisition of a statistically adequate abundance measurement. This event was followed by the large flares of 22 and 24 October (DOYs 295 and 297). The HIC abundance measurements can be used to confirm that the B&S[1] techniques also apply to these flares, which are substantially larger than any in their sample.

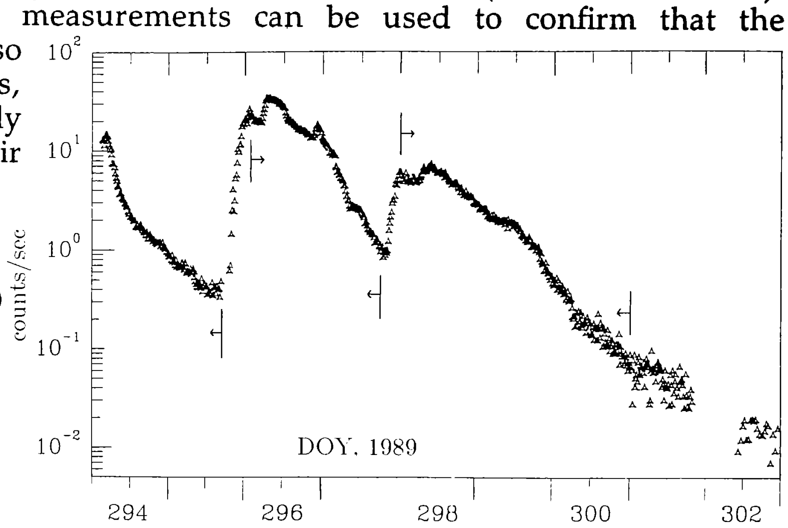

Figure 1: Count rate versus time (day of year) for the three flares analyzed here. Selected periods indicated with vertical tick marks.

INSTRUMENT: The Galileo HIC is described in Garrard *et al.*[2] Briefly, there are two solid-state, range/energy/energy-loss telescopes (called B and E) similar to the Voyager CRS Low Energy Telescopes,[3] with minor modifications to optimize them for the Galileo objective of monitoring high energy heavy ions (ions with the potential of of causing "single event upsets" in the spacecraft electronics) in the Jovian magnetosphere. Here, only stopping particles are considered (≤70 MeV/nucleon), and emphasis is placed on the 9.5 to 15 MeV/nucleon range, for which all ions stop in the same range detector. The energy loss is measured twice, once in each of the first two detectors; residual energy is measured in the third. We require consistency between the energy losses in the first and second detectors to eliminate nuclear interactions, edge effects, etc.

MEASUREMENTS: Figure 1 shows the count rate of ions with Z > 6 and kinetic energy ≥4 MeV/nuc as a function of time. The three time intervals analyzed here are indicated by vertical bars. Figure 2 shows a histogram of estimated Z for particles in the third flare which meet the consistency criteria and the energy selections. The vertical scale is expanded to emphasize the rarer elements. The $_6$C and $_8$O peaks are off scale at 1072 and 2953 counts respectively. Of the elements with abundances reported here, only $_{11}$Na, $_{13}$Al, and $_{24}$Cr have any significant possibility of contamination from more abundant neighboring elements. For those three elements, element identification is based on analysis of both energy loss signals available for each event rather than on the average used for the histogram (see ref. 4 for details), so that resolution is slightly better than what is seen in Figure 2. We estimate the resulting residual contamination of the abundances of these three rare elements is ≤10%. The abundance labeled $_{26}$Fe includes elements 25, 26, 27 and 28.

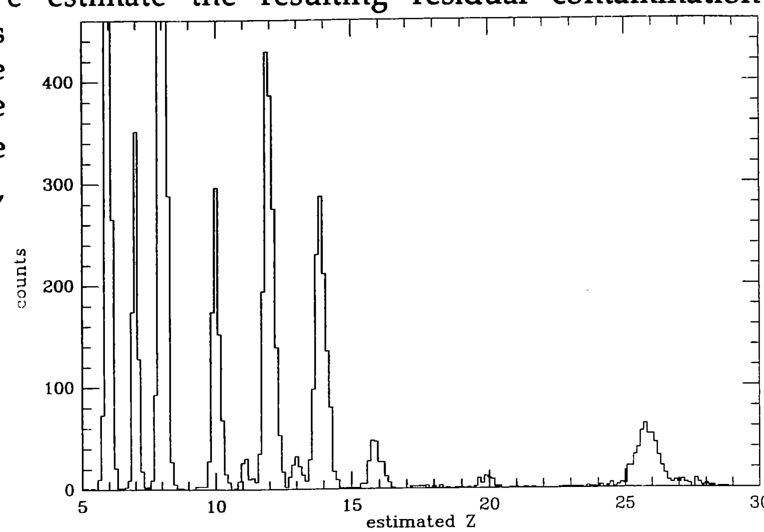

Figure 2: Histogram of estimated atomic number, Z. Note that the Na and Al peaks are clearly visible.

ANALYSIS: The elemental abundances from each flare are normalized to the abundance of $_{14}$Si and normalized again to solar model abundances. When these ratios of ratios are plotted versus Q/M[5], they exhibit the previously reported[1] power-law Q/M fractionation for the low-FIP elements. A power-law fit to the low-FIP abundances for a given flare is used to determine the Q/M-dependence. The abundances of *all* elements are then corrected for Q/M fractionation according to that power law, normalizing again to Si. An example of such a plot is shown in Figure 3 for the 3rd flare.

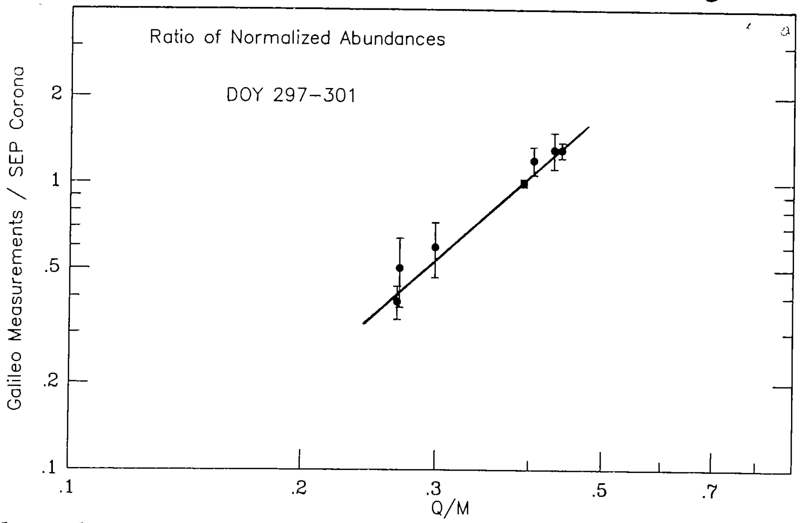

Figure 3: Ratios of normalized abundances as a function of ion charge to mass ratio. In this plot, our new measured abundances for the 3rd flare are compared to the B&S SEP-derived corona.

The three flares here have power-law slopes of 0.5 ± 0.25, 2.5 ± 0.26, and 2.3 ± 0.26 in time order. The range found by Breneman[4] was from -2 to +4.7, with most flares between 0 and 2.4.

In Figure 4a, these corrected abundances are compared to the B&S SEP-derived corona with FIP as the organizing factor. Figure 4b shows a similar comparison with Anders and Grevesse[6] corona.

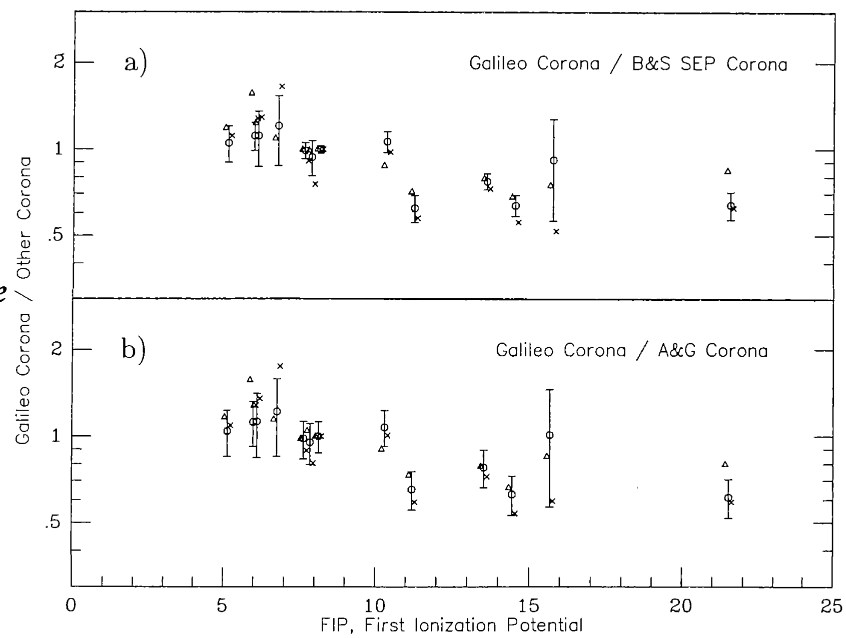

Figure 4: Galileo SEP-derived coronal abundances divided by (a) B&S SEP-derived coronal abundances or (b) Anders and Grevesse coronal abundances versus First Ionization Potential, FIP. Typical error bars are shown.
∇ first flare;
× second flare;
○ third flare.

DISCUSSION: Even these very large flares have the the same Q/M fractionation relative to coronal abundances discussed by B&S. The Q/M fractionation likely results from electromagnetic processes in acceleration and transport of the particles, after their charge state Q is established in the corona. The SEP abundances after Q/M correction should represent the coronal abundances and have been compared to spectroscopic coronal abundances.

Figure 5 compares to Anders and Grevesse[6] photospheric abundances. We see the familiar step function[7], similar to what is observed for source abundances of galactic cosmic rays. The location of the step and the height of the step are similar to that shown in B&S. They report a typical fractionation factor of 0.2 for high-FIP elements; our factor of ~0.15 is within the range of variability B&S observed among different flares. (This difference is also visible in Figure 4.) The FIP-fractionation is thought to derive from differences in transport of ionized (low-FIP) and un-ionized (high-FIP) material from the photosphere to the corona.

Additional flare observations from Galileo are expected over the next few years. We hope that an increased sample of observations will allow more detailed study of both the Q/M- and FIP-fractionation effects.

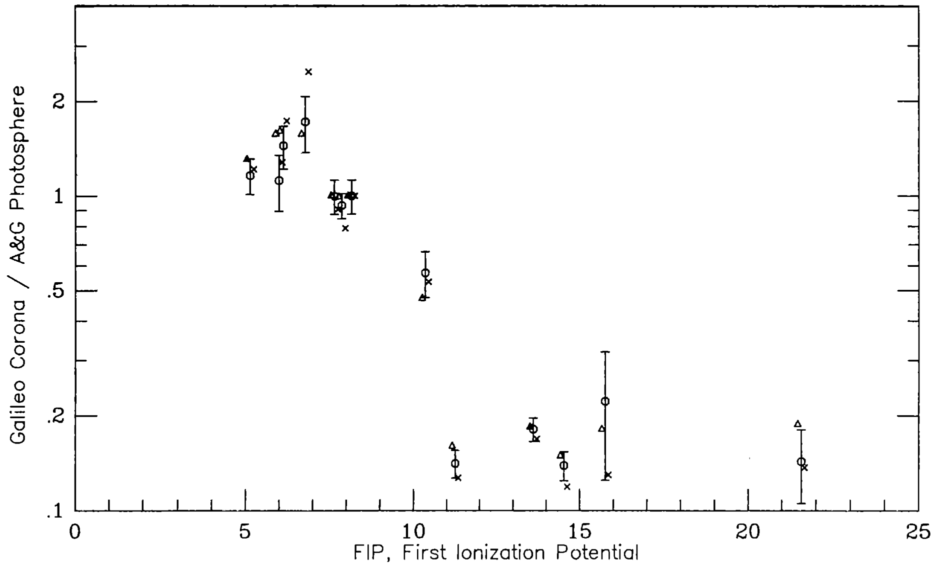

Figure 5:
Galileo SEP-derived coronal abundances divided by Anders and Grevesse photospheric abundances versus FIP. Symbols as in Figure 4.

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