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Determination of the Ionic Charge States of SEPs Using the University of Chicago IMP-8 Instrument

W. Dietrich[1] and C. Lopate[1]

[1] *The University of Chicago, Enrico Fermi Institute, Laboratory for Astrophysics and Space Research, Chicago, IL 60637-1460, USA*

Abstract

We use a new method to calculate the mean ionization charge state of solar energetic particles (SEPs) observed with the University of Chicago Cosmic Ray Nuclear Composition experiment on the IMP-8 satellite. The method, using the time to maximum flux, is demonstrated for several gradual SEP events, including the events on 29 September 1989, 19 October 1989, 24 October 1989, and 6 November 1997. Mean ionic charge states are deduced for heavy ions with energies in the range ~10-500 MeV/nucleon. The ionic charge determination is made only during the onset of the SEP events. These mean charge states agree well with previous measurements for SEP events both at low energy (~0.5-4 MeV/nucleon reported by ISEE-3) and at higher energies (~200-500 MeV/nucleon reported by LDEF). The mean ionic charge states are then used to determine an average temperature and source region for these particles.

1 Introduction:

The ionic charge states of solar energetic particles (SEPs) can provide important information about the location of the source material of these energetic particles as well as the subsequent acceleration processes and their propagation through interplanetary space. Both acceleration and transport processes for energetic particles depend on the particles rigidity. Thus a knowledge of the ratio A/Q is essential for a proper comparison between measurements of accelerated charged SEPs at Earth and the theoretical models for their transport. Also, since the ionic charge states of these charged particles do not vary during their passage through interplanetary space [Hovestadt et al., 1984], a knowledge of these ionic charge states as determined at Earth can be used to infer conditions for the plasma at the source region of these ions.

We report here a new technique to determine the charge state of energetic ions measured at Earth. Our technique, using the time-to-maximum intensity, is fairly simple in execution and can easily use measurments from multiple spacecraft. Using this technique we have been able to determine the ionic charge state of energetic Fe ions during four large "gradual" SEP events. Our results are consistent with previous reports of ionic charge states of Fe during "gradual" events, and indicate that the source region for these accelerated particles is the solar corona, with a temperature of about $2\text{x}10^6$K.

2 Instrumentation:

The bulk of the data come from Chicago's Cosmic Ray Nuclear Composition (CRNC) experiment on the IMP-8 satellite [Garcia-Munoz, Mason and Simpson, 1977]. We supplement our CRNC data with data from the Goddard Space Flight Center's IMP-8 detector [Teegarden et al., 1975] and data from the NOAA GOES satellites. All these satellite data use a standard energy loss (dE/dx) vs. residual energy (E) analysis to determine the atomic number of each stopping ion. The full range of response to ions of all the satellites is ~0.5-400 MeV/nucleon. Lastly we use the ground based neutron monitor at Climax, CO to get a high energy proton response, ~4 GeV mean energy for protons.

3 Data Analysis:

The method we use to determine the ionic charge states of the various SEPs seen at Earth is based on the time-to-maximum (TTM) flux of the diffusive part of the SEP event. We calculate a charged

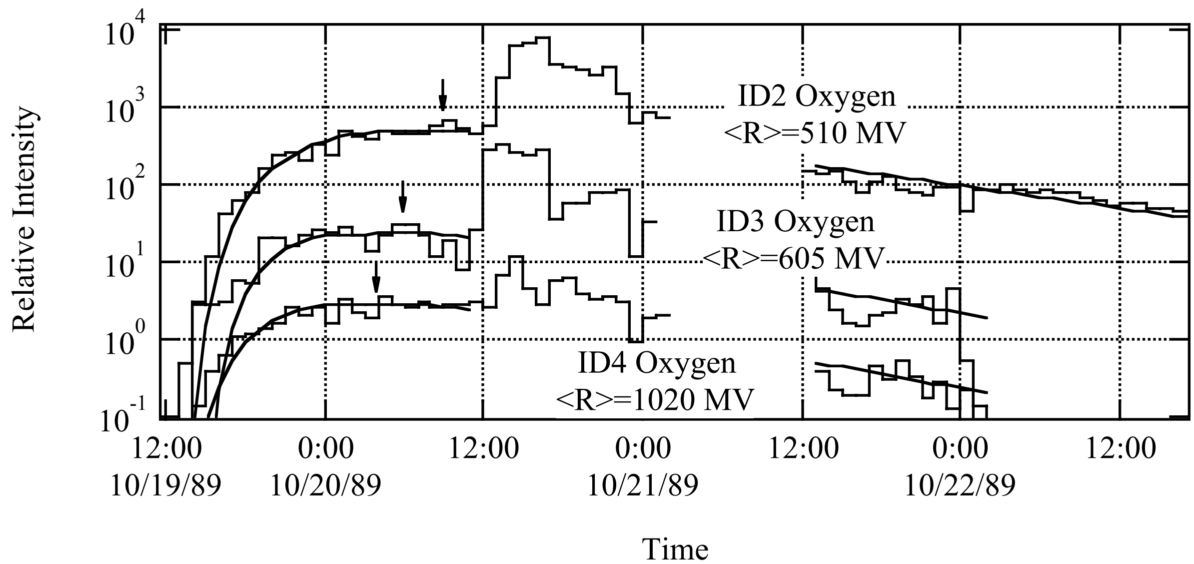

Figure 1. Time intensity profiles of the three oxygen rates measured by the Chicago CRNC instrument on IMP-8 for the October 19, 1989 SEP event. Arrows mark the best-fit time of maximum intensity of the diffusive portion of the event for each different rate.

particle rate for several energies of various elements observed at Earth during the SEP events. Once we have these rates, we next calculate the time of the maximum intensity for each rate. We are interested only in the diffusive part of the SEP event, so when a local traveling shock is observed by the instruments, we do not include the local shock accelerated particles in the calculation of the TTM, even though frequently the shock is associated with a higher flux of particles. As an example, Figure 1 shows the time profile of the O flux at three different energies during the October 19, 1989 SEP event. Notice that the local shock accelerated particles are ignored in this determination. In order to attain a self-consistent TTM, we fit the rate profiles with a functional form: $r(t) = A/t * \exp(-B/t) * \exp(-t/C)$, where A, B and C are fit parameters, t is the time in hours and r(t) is the rate at time t.

We have carefully corrected our rates for short coverage periods, readout deadtime, and pulse pile-up in the detectors, especially near the time of maximum fluence for each event. These corrections are on the order of at most 20% for the four events studied here. In the four SEP events we study, the time of maximum intensity is unaffected by the corrections to within 1 hour, which is our minimum averaging interval.

Once we have the time of maximum flux of the diffusive part of the SEP event we calculate the TTM by subtracting from that time the time that radio bursts (type II and type IV) are first observed. We then plot log(TTM) vs. log(R) where R is the particle rigidity (as shown in Figures 2A-2D). By adjusting the ionic charge states of the various elements we have observed that we can create a linear relationship between log(TTM) and log(R), irrespective of the particle species.

When we derive the relationship between TTM and rigidity we assume that He is fully stripped, and then choose ionic charge states for the heavy ions such that C, O and Fe follow the same relation as He. For C and O deviations from fully stripped to a state with a single electron remaining do not make appreciable changes (~20% maximum change) in the C and O rigidities. For Fe; however, the charge can vary between ~6 and ~26 [e.g. Luhn et al., 1987] which can result in between a factor 2 to 4 change in the rigidity of the Fe. Thus this analysis technique is most useful for determining the charge state of Fe during these CME driven events. We allowed the charge states of C and O to vary in 1/2 charge unit steps from 5 to 6 and 7 to 8, respectively; the Fe was allowed to vary from 0 to 26 in 1/2 charge unit steps. We chose the charge states which gave the minimum least-squares fit to a linear

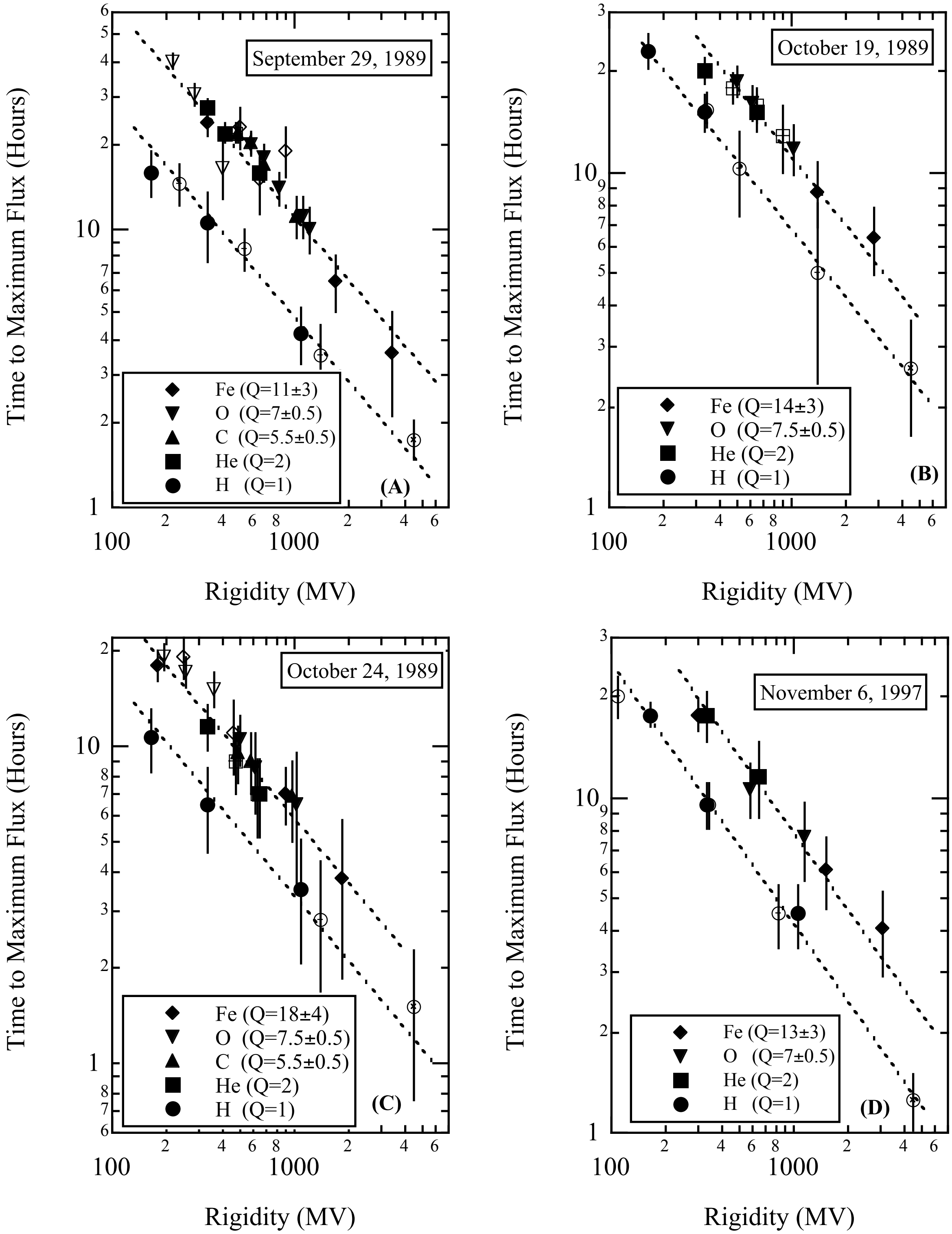

Figure 2. Best fits to the Time-to-Maximum for four large CME driven SEP events. Charge states are determined by finding the Q which allows the linear fit with the smallest least squares deviation. Circles= H, Squares= He, Down-Triangles= O, Up-Triangles= C, Diamonds= Fe. Solid= Chicago, Open= Goddard, Open-Pluses= GOES, Open-Crosses= Climax.

relationships between log(TTM) and log(R). The errors in <Q> were determined from the same weighted least-squares fit, but are rounded to the nearest 1/2 charge unit.

4 Discussion:

Our analysis assumes that for a given SEP event, all the heavy ions (He and greater) have the same TTM vs. rigidity relationship. We also assume that protons show the same relative change in TTM vs. rigidity, but the TTM is offset by about 2-4 hours, the protons arriving before all other ion species of similar rigidity. We attribute this difference to protons interacting with their own self-generated wave turbulence, thus not propagating as test particles through the accelerating region, while all other species can be treated as test particles interacting with the turbulence generated by the protons.

As can be seen from the plots in Figure 2, our analysis indicates that average ionic charge state of Fe, in the energy range ~20-400 MeV/nucleon for these four event is $\langle Q \rangle = 14 \pm 3$; however, there is significant variability in the ionic charge state determination from event to event. This is consistent with earlier reports [e.g. Leske et al., 1995 and Tylka et al., 1995] at similarly energies and also at the lower energies [Luhn et al., 1987] for "gradual" SEP events. Our ionic charge state calculation for Fe is not consistent with that calculated for "impulsive" SEP events $\langle Q \rangle = 20.5 \pm 1.2$ [Luhn et al., 1987]. Our determination of the ionic charge state of Fe is consistent with a mean plasma temperature of $\sim 2 \times 10^6$K [Arnoud & Raymond, 1992] suggesting that the source for the accelerated heavy ions in "gradual", CME driven SEP events is probably ambient coronal material, not the hot flare plasma.

Our technique shows a new method for the determination of the ionic charge states of high energy SEPs. Since we are using only the diffusive portion of the events, it may be that the analysis breaks down at extremely low energies. Also, since we are using the early portion of the SEP events, this method cannot be used to determine whether the charge states of the various species change as a function of time; indeed, we must assume that for the charge states do not change during the period of analysis, which can be as great as ~20 hours for heavy ions in some cases. Also, because of the inherent uncertainty in determining the exact time of maximum flux (often the error can be as much as 2 hours), the uncertainty in the calculated <Q> is generally around 3 charge units at iron. Advantages of this technique are that we do not require absolute intensities for any of the various ion species, thus intercorrelation between different measuring devices is simple. Also, we do not require a well-defined externally applied magnetic field [Tylka et al., 1995] to order the ions.

While our analysis is consistent with previous work, we have only been able to analyze a few "gradual" SEP events. The IMP-8 instrument does not have a large enough geometrical factor to analyze small events or to look at some of the rarer elements. We hope to apply this technique with more modern instrument data to determine charge states of other ions and to determine whether "impulsive" SEP events show the same relationship between TTM and rigidity.

5 Acknowledgments:

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