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High-Energy Solar Fe Ions in the 29 September 1989 Ground Level Event

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Abstract

Lovell, Duldig, and Humble (1998) have recently published a detailed analysis of the world-wide neutron monitor network's response in the 29 September 1989 Ground-Level Event (GLE). We compare their proton spectra to simultaneous measurements of solar Fe ions at ~50 - 1000 MeV/nuc from the University of Chicago's Cosmic Ray Nuclear Composition (CRNC) Experiment on *IMP-8*. These measurements revealed the hardest spectrum of high-energy solar Fe ions ever observed. When examined as a function of rigidity, the Fe nuclei do not appear to be sufficiently numerous to complicate interpretation of the neutron-monitor results, even after accounting for their partially-ionized charge state (~14). However, at very high *total* energies, the Fe spectrum is much harder than the proton spectrum, and protons and Fe appear to make comparable contributions to the so-called "all-particle" spectrum. Thus, CME-driven shock acceleration in this very large solar particle event may be producing the same spectral differences and evolution in composition which are believed to be caused by supernova-shock acceleration at the knee of the Galactic cosmic ray spectrum.

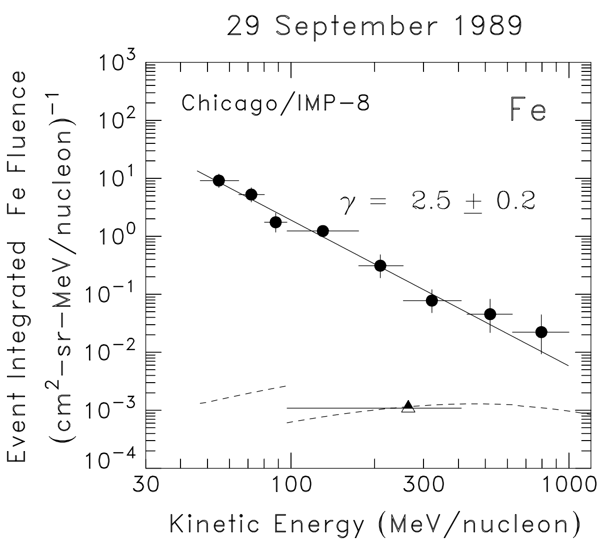

Figure 1: Event-integrated Fe fluence from CRNC/*IMP-8*. Power-law fit (solid-line) and residual Galactic background (dashes) are also shown. Half-filled triangle is the observed 27-day averaged solar-quiet Fe intensity used to normalize the background. The discontinuity in the background curve is due to the longer integration time used at low energies.

1 Fe in the 29 September 1989 Event

The 29 September 1989 solar particle event began with a very large coronal mass ejection on the west limb of the Sun, with a projected speed of 1828 km/s (Kahler 1994). At this speed, the CME undoubtedly drove a powerful shock capable of producing large intensities of high-energy particles. *GOES* observed an X 9.8 x-ray flare in connection with this event, but there was no Hα flare on the visible solar disk. NOAA has associated this event with Active Region 5698, which was located at ~W98 at the time. Solar wind observations were spotty during this event, but Lovell et al. (1998) have suggested that an unusually slow solar wind speed (down to ~280 km/s on 25-26 September) may have facilitated good connection to strong parts of this CME-driven shockfront, in spite of their far-western location.

Figure 1 shows the event-integrated Fe spectrum for this event, which is well fit (reduced χ^2 ~0.7) by a power law with spectral index γ =2.5 ± 0.2. As previously mentioned, this is the hardest solar Fe spectrum ever observed. It is also considerably harder than this event's oxygen spectrum, which has

$\gamma = 3.9 \pm 0.3$ (Tylka, Dietrich, & Boberg 1997; Tylka & Dietrich 1999).

Figure 2 shows the time-intensity profile for six-hour-averaged Fe ions from the CRNC/*IMP-8*. Tightly-clustered arrival times provide a clear indication of the solar origin of the high-energy ions. For example, the >432 MeV/nuc Fe ions (not shown in Figure 2) all arrived between 13 and 17 UT. Nevertheless, a concern at high energies is possible Galactic cosmic ray (GCR) background. In order to minimize such background, the accumulation for >100 MeV/nuc Fe was ended after 28 hours, but continued for another ~3 days for lower energies. The dashed lines in Figure 1 show estimates of the *residual* GCR background. (See Tylka & Dietrich 1999 for further details.) Even at the highest energies, the Fe intensity is more than an order of magnitude above GCR background.

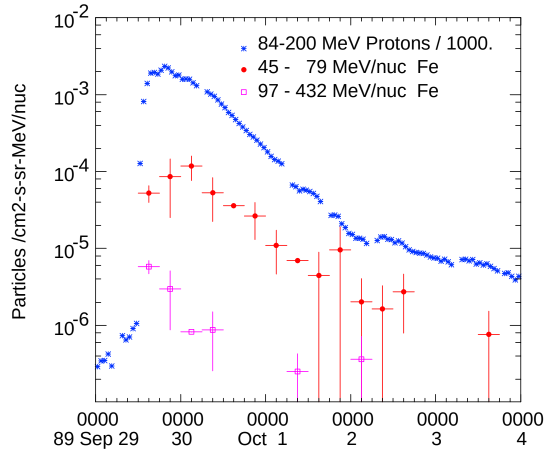

Figure 2: Six-hour-averaged Fe intensities from CRNC/*IMP-8*. Also shown are hourly proton-intensities from *GOES*, multiplied by a factor of 0.001. After 30 September, *IMP8* datapoints without vertical error bars are estimated values, from exponential fits to the timeline, used to correct for datagaps when evaluating the event-integrated fluence.

2 Comparison to GLE Proton Spectra

From 13-17 UT on 29 September (the period appropriate for comparison with Lovell et al.), the hourly-averaged Fe intensity at 97-432 MeV/nuc was constant to within ~30% statistical uncertainty at 9 x 10^{-6} / cm^2-s-sr-MeV/nuc. We use this value to re-normalize the event–integrated spectrum from Figure 1 when comparing to the GLE proton intensities.

In analogy with the GCR "all-particle" spectrum, Figure 3 shows the Fe and proton intensities as a function of *total energy per* ***nucleus***, *not* energy per ***nucleon***. The proton spectrum[1] in Figure 3 is averaged over 13-14 UT (J. Lovell, private communication). The Fe spectrum is clearly harder than the proton spectrum. Moreover, the Fe/p changes dramatically, so that the all-particle spectrum becomes dominated by Fe above 10 GeV.

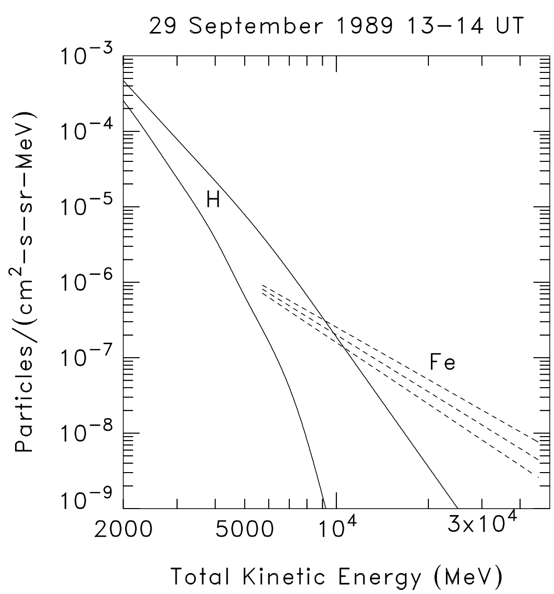

Figure 3: *IMP-8* Fe and Lovell et al. (1998) proton spectra vs. total energy per particle. Solid curves are estimated upper and lower bounds on the protons at 13-14 UT. Dashed curves show Fe, allowing for uncertainty in the fitted spectral index. The Fe curves extend only from 100 MeV/nuc through the energies actually measured.

[1] These proton spectra come from Figure 4 of Lovell et al. (1998). The upper-bound proton spectrum shown in that figure was actually truncated at 10 GeV. For the purposes of this figure, we have assumed a power-law extension beyond 10 GeV.

3 Fe Contribution to Neutron Monitor Response?

Neutron monitors (NMs) register increases in the atmospheric neutron flux. These increases are *attributed* to changes in the top-of-the-atmosphere *proton* flux above a certain cutoff rigidity, which is determined by the monitor's location. Given the large Fe/p ratio in Figure 3, one might worry that neutrons generated by Fe nuclei could be contributing to the NM response. If this were the case, the NM results would have to be re-interpreted and revised.

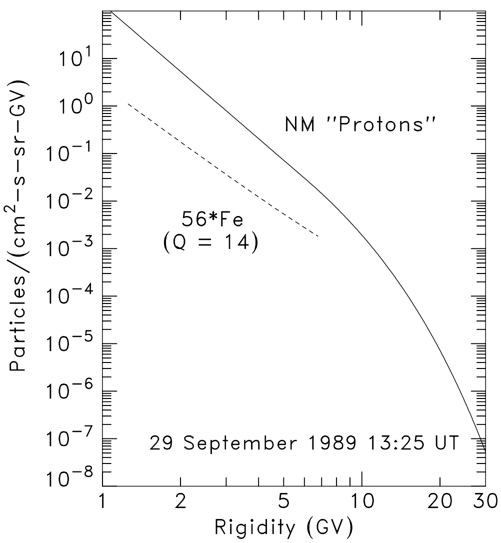

Figure 4: Fe and proton intensities as functions of rigidity. Fe rigidities are evaluated assuming ionic charge Q=14. The Fe intensity is also multiplied by a factor of 56, as discussed in the text. The solid proton curve is the Lovell et al. spectrum at 13:25 UT.

Figure 4 compares the NM "proton" and CRNC/*IMP-8* Fe intensities as a function of rigidity. For this comparison, the Fe nuclei were assumed to have an ionic charge state of 14, as directly measured by geomagnetic-penetration studies in this event (Tylka et al. 1995). The Fe intensity in Figure 4 is multiplied by a factor of 56, to very crudely account for additional neutron production from an Fe projectile. This factor is likely to be an overestimate: the nuclear interaction mean free path of Fe nuclei in air is ~10 g/cm^2, and most of the Fe at these energies will slow down or even stop in the atmosphere before they interact.

For energies at which CRNC/*IMP8* has measured the Fe spectrum (dashed line in Figure 4), the Fe contribution is at most ~10% of the proton signal. However, if the Fe spectrum in Figure 4 were to continue to higher rigidities without rolling off, the Fe contribution might be significant. This possibility deserves further study. (See Dietrich & Lopate 1999.)

Finally, it is tempting to note the difference in hardness between the proton and Fe rigidity spectra in Figure 4. However, caution is necessary here since propagation effects are not entirely negligible. In particular, Lovell et al. (1998) also show a proton spectrum at 12:15 UT, before arrival of the Fe ions. Although the proton intensities at the highest energies vanish within a few hours, this earlier spectrum is significantly harder than the proton spectrum shown here. A fairer comparison between the proton and Fe rigidity spectra would integrate over a longer range of arrival times in order to include the earlier protons. This integration would reduce -- but probably not remove -- the difference in hardness between the proton and Fe rigidity spectra.

4 Discussion

The endpoint-energy of shock acceleration depends upon several factors, including shock lifetime and particle containment in the shock region and perhaps some larger propagation volume as well. It is generally believed that these factors are involved at the so-called "knee" of the Galactic cosmic-ray all-particle spectrum at ~10^{15} eV. Presently available data[2] suggest that the GCR composition (in terms of total energy per particle) in this region evolves toward heavy-ion enrichment and that the heavier ions have

[2] See Cherry 1997 for a recent review.

harder spectra than protons. (In fact, hints of these spectral differences are also seen at energies well below the knee.)

The solar proton and Fe comparisons in Figure 3 are in some sense trivial, since we are no longer comparing on the more appropriate “energy per nucleon” scale. However, we are nevertheless examining the composition and spectra near the highest proton-energies attained in this CME-driven shock. The similarities between the GCR “knee” and these solar particle observations make it tempting to speculate that they are due to a common feature of shock acceleration, albeit operating at much lower energies in this case [Reames 1999].

One explanation for the composition changes at the knee is that the finite lifetime of the supernova-blast-wave shock limits the attainable energy per particle, and that this limit is proportional to the charge (Gaisser, 1990). Such finite-lifetime effects apply to CME-driven shocks, so perhaps there is nothing surprising in the comparisons we have presented here. On the other hand, in the GCR case, one must consider not only the finite shock lifetime and containment in the shock region but also possible distortions introduced by escape from the Galaxy. No analogous escape effect complicates interpretation of the solar particle observations. Further study of solar particle composition and spectra at the highest possible energies may therefore offer new insights into the physics of shock acceleration which will complement studies of the GCR knee.

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