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RESULTS FROM THE HEAVY IONS IN SPACE (HIIS) EXPERIMENT ON THE IONIC CHARGE STATE OF SOLAR ENERGETIC PARTICLES

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SUMMARY

It has long been known that low-energy solar energetic particles (SEPs) are partially-ionized. For example, in large, so-called "gradual" solar energetic particle events, at ~1 MeV/nucleon the measured mean ionic charge state of Fe ions is $<Q>= 14.1 \pm 0.2$, corresponding to a plasma temperature of ~2 MK in the coronal or solar-wind source material. Recent studies, which have greatly clarified the origin of solar energetic particles and their relation to solar flares, suggest that ions in these SEP events are accelerated *not* at a flare site, but by shocks propagating through relatively low-density regions in the interplanetary medium. As a result, the partially-ionized states observed at low energies are expected to continue to higher energies. However, up to now there have been no high-energy measurements of ionic charge states to confirm this notion.

We report here HIIS observations of Fe-group ions at 50-600 MeV/nucleon, at energies and fluences which cannot be explained by fully-ionized galactic cosmic rays, even in the presence of severe geomagnetic cutoff suppression. Above ~200 MeV/nucleon, all features of our data -- fluence, energy spectrum, elemental composition, and arrival directions -- can be explained by the large SEP events of October 1989, *provided* that the mean ionic charge state at these high energies is comparable to the measured value at ~1 MeV/nucleon. By comparing the HIIS observations with measurements in interplanetary space in October 1989, we determine the mean ionic charge state of SEP Fe ions at ~200-600 MeV/nucleon to be $<Q> = 13.4 \pm 1.0$, in good agreement with the observed value at ~1 MeV/nucleon. The source of the ions below ~200 MeV/nucleon is not yet clear.

Partially-ionized heavy ions are less effectively deflected by the Earth's magnetic field than fully-ionized cosmic rays and therefore have greatly enhanced access to low-Earth orbit. Moreover, at the high energies observed in HIIS, these ions can penetrate typical amounts of shielding. We discuss the significance of the HIIS results for estimates of the radiation hazard posed by large SEP events to satellites in low-Earth orbit, including the proposed Space Station orbit.

Finally, we comment on previous reports of low-energy below-cutoff Fe-group ions, which some authors have interpreted as evidence for partially-ionized galactic cosmic rays. The LDEF flux levels are much smaller than the corresponding fluxes in these previous reports, implying that the source of these ions has an unusual solar-cycle variation and/or strongly increases with decreasing altitude.

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INTRODUCTION

Galactic cosmic rays are generally believed to be bare nuclei, fully stripped of all orbital electrons. One of the primary goals of the Heavy Ions in Space (HIIS) experiment is to investigate possible sources of partially-stripped heavy ions. The study of such ions is of astrophysical interest, especially at high energies where the cross-section for electron-stripping greatly exceeds the cross-section for electron pick-up. In this case, a measurement of the mean ionic charge state significantly constrains the amount of matter traversed by the ions, thereby helping to identify their source and the mechanism by which they have been accelerated to high energies. Two well-known sources of partially-ionized heavy ions are anomalous cosmic rays[1] and (at least at low energies) solar energetic particles (SEPs)[2,3,4].

Partially-ionized heavy ions are also of potential practical importance: their lower charge state gives them higher magnetic rigidity than fully-ionized cosmic rays of the same kinetic energy. As a result, partially-ionized heavy ions can penetrate to orbits which are largely shielded from cosmic rays by the Earth's magnetic field. Partially-ionized ions, at least in some orbits and under certain conditions, may thus constitute an important component of the ionizing-radiation environment encountered by humans and hardware in low-Earth orbit.

EXPERIMENT DESCRIPTION

A detailed description of HIIS has been published previously[5,6]. The HIIS detector uses thick stacks of plastic track detectors, mounted on the space-facing end of LDEF, with an unobstructed view of the sky and efficient particle detection down to zenith angles of ~70°. The detectors are completely passive: that is, they provide no information on when individual ions were collected during LDEF's 69 months in space. Conclusions about the origin(s) of ions observed in HIIS must therefore be deduced from other characteristics of the data, such as fluence, energy spectrum, composition, and arrival directions. HIIS is divided into eight modules, each of which consists of a main stack (comprising primarily ~300 10-mil-thick sheets of CR-39[2*] sealed in 1 atm of dry air) and a top stack (consisting of 22 5-mil thick sheets of Lexan[3*], exposed in vacuum.) The collecting power of the total instrument is approximately 2.0 m^2-sr, making HIIS the second-largest cosmic-ray experiment ever flown in space. In this paper, we present data collected from ~60 CR-39 sheets at various depths in the main stack of one module. Preliminary results on low-energy heavy ions from small portions of three top stacks are presented by Kleis et al. in these Proceedings[7].

OBSERVATIONS OF STOPPING HEAVY IONS

We have used a combination of manual and automated scanning to locate stopping tracks in the CR-39 detector sheets. (A detailed description of the detection method, the calibration technique, and track-fitting procedures is given in Ref. 8.) Fig. 1 shows the V_T/V_B vs. residual range measurements from stopping tracks located in CR-39 sheets near the top of one detector module. The strong accumulation

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[2*] CR-39 is poly diethylene glycol bis-alyl carbonate and was invented at Pittsburgh Plate Glass's Columbia Resin Laboratory in Barberton, OH.

[3*] Lexan is the trade name for bis-phenol A polycarbonate, as sold by General Electric, Pittsfield MA. It is also sold under the tradenames of Tuffak and Rodyne-P.

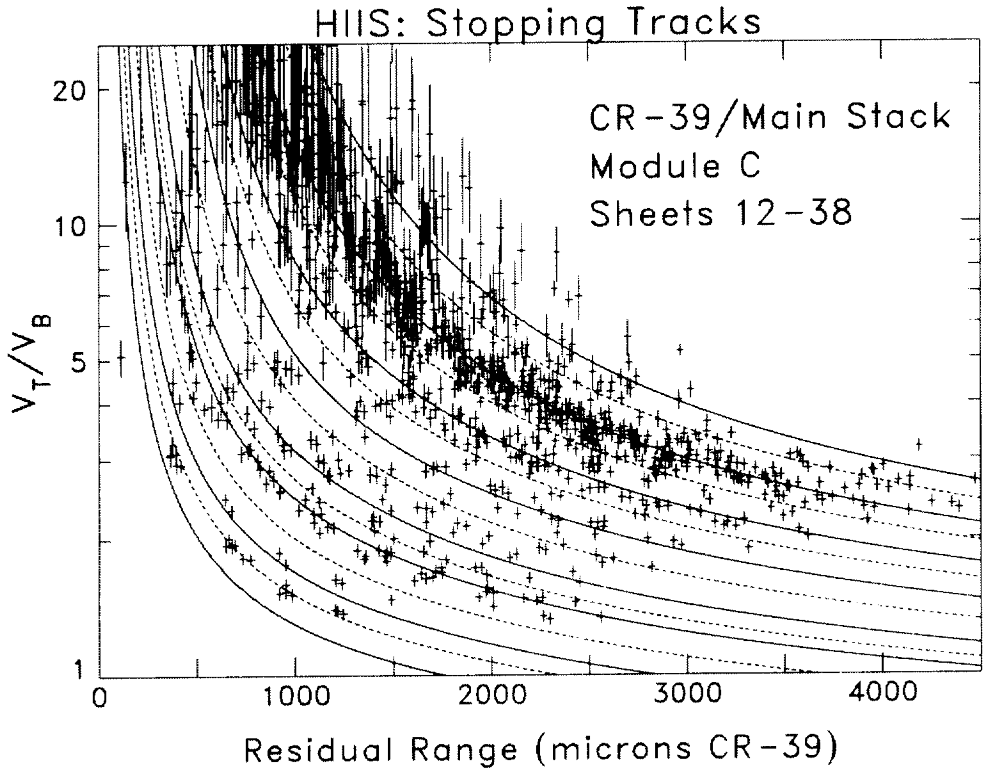

Figure 1: V_T/V_B vs. residual range measurements from stopping tracks found in CR-39 near the top of one module. The plot contains 1028 measurements from 97 cosmic-ray tracks incident upon the detector from space. The response curves are for elements with atomic numbers Z = 14-28, with solid and dashed curves for even and odd elements, respectively.

of tracks was identified as Fe. To derive an internal calibration of the detector we used a subset of these Fe tracks, as well as a few lighter tracks to extend the calibration to $V_T/V_B < 2$. This calibration was then used to generate the elemental response curves shown in Fig. 1.

For each stopping track we typically had ~10 independent V_T/V_B measurements spread over the last ~3500 microns of the particle's range. Each set of V_T/V_B measurements was fitted to the detector response function using a χ^2 minimization to determine the particle's atomic number, Z. Fig. 2 shows the histogram of fitted atomic numbers for particles found throughout the detector stack. The strong Fe peak is clearly seen[4*], and a gaussian fit to this peak gives $\sigma = 0.43 \pm 0.04$ charge units. Fig. 2 is uncorrected for Z-dependent acceptance effects. In particular, our scanning method generally does not find ions at $Z < 14$, and the acceptance increases gradually between Z=14 and Z=20. At larger Z the acceptance is constant to within approximately 15%.

Composition. Fig. 3 examines the composition of the stopping heavy ions in more detail. It shows the sub-Fe to Fe ratio (defined here as $\Sigma(21 < Z < 25)/\Sigma(Z \geq 25)$, because of the detector's modest charge resolution) as observed at various depths in the detector stack. These depths correspond to stopping Fe

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[4*] In an earlier status report on the HIIS experiment[8] we showed a charge histogram which had a strong peak at Z=25. Those data came from a detector module in which there had been a severe thermal blanket failure, probably near the end of the mission. This failure apparently caused a shift in the detector calibration. The data reported here are from a second module, in which the thermal blanket returned from space nearly intact.

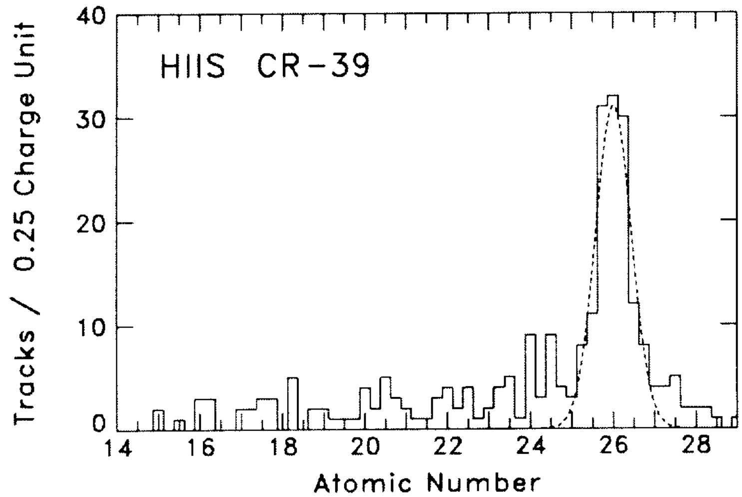


Figure 2: Histogram of fitted atomic numbers. Also shown is a gaussian fit to the Fe peak with σ = 0.43.

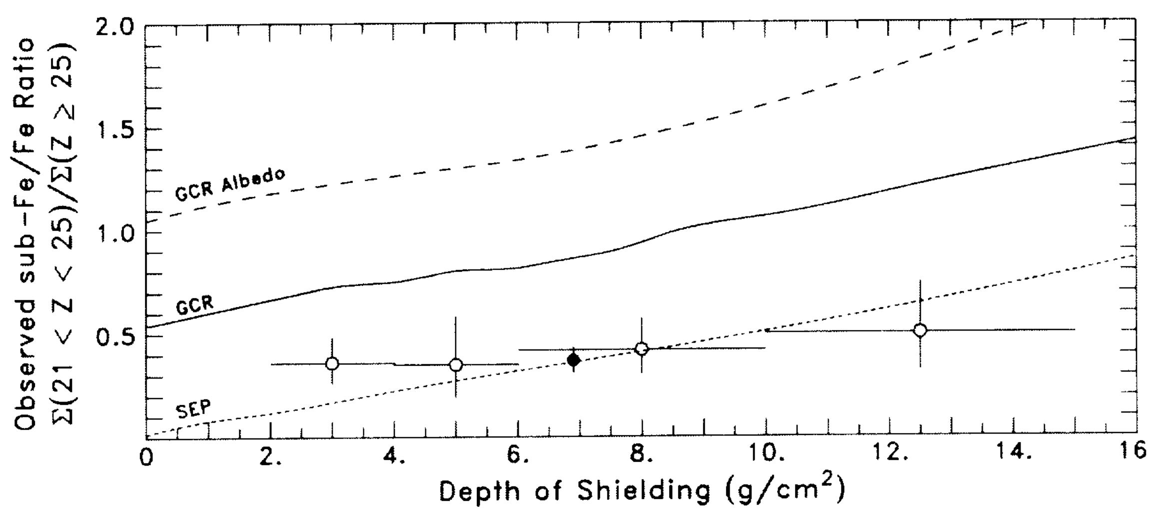


Figure 3: Sub-Fe/Fe ratio of stopping tracks, as observed under various depths of shielding. The open circles are for subsets of the data sample. The filled circle is for the combined dataset of all tracks, with abscissa at the mean shielding depth. The curves show the expected composition for various sources, after taking into account fragmentation in the detector.

ions with incident energies of ~185 - 650 MeV/nucleon at the top of the detector. Small corrections (~5%) have been applied to the measurements, to account for the weak Z-dependence of the detector acceptance.

The composition vs. depth curves in Fig. 3 were calculated by first adjusting the incident spectrum of the hypothetical source (SEPs, galactic cosmic rays (GCRs), or GCR albedo) to match the Fe spectrum in Fig. 5 below. Each hypothetical source was then propagated to various depths in the detector stack using a nuclear transport code[9]. Fig. 3 shows that the observed composition is consistent with an incident source with a very small proportion of sub-Fe ions. In fact, the incident composition is consistent with that of SEPs, with a sub-Fe/Fe ratio of a few percent before fragmentation in the detector. But the observed composition is inconsistent with that expected for GCRs (with an incident sub-Fe/Fe ratio of ~0.5 before additional fragmentation in the detector) or GCR albedo (with even more sub-Fe ions due to fragmentation in the atmosphere before reaching LDEF).

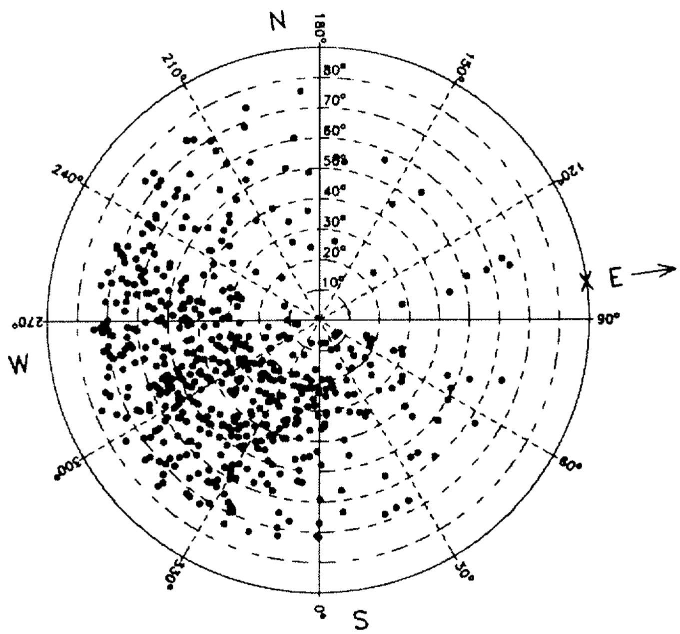
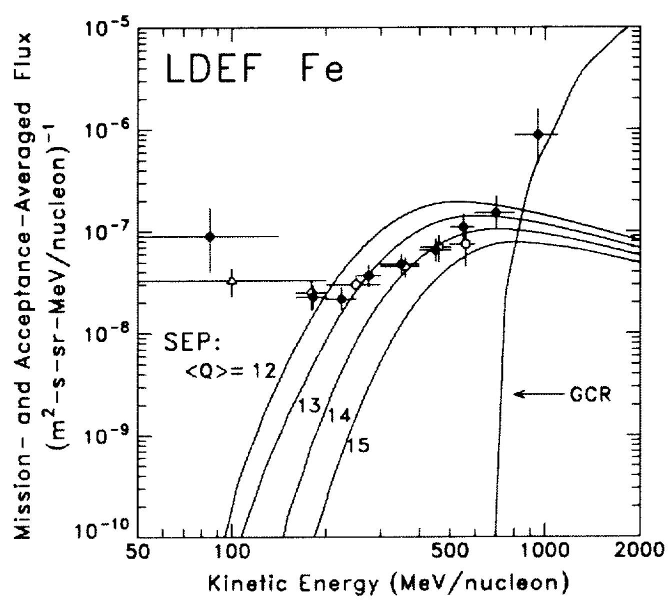


Figure 4: Arrival directions of particles incident from space. The radial coordinate is the zenith angle, and the azimuth angles are as given in the LDEF coordinate system. The small arrow indicates the LDEF velocity vector. The azimuth labels (N,E,S,W) apply at the northern and southern extremes of the orbit, when the satellite is moving due east. This figure contains data from two HIIS modules.

Figure 5: LDEF Fe flux measurements from HIIS (filled circles) and the Kiel[10,11] (open triangle) and Siegen[12] (open circles) experiments. The HIIS data point at 85 MeV/nucleon comes from Kleis et al. measurements[7] in the Lexan top stack. Additional Kiel data points for *trapped* Fe ions below 50 MeV/nucleon are not shown here. The curves show the expected contributions for galactic cosmic rays (GCR) and the solar energetic particle (SEP) events of September-October 1989, as calculated with the indicated values of the mean ionic charge state, <Q>.



Arrival Directions. Fig. 4 shows the arrival direction distribution of the stopping particles. The distribution is highly anisotropic, with arrival directions centered about the southwest, apparently the direction of lowest geomagnetic cutoff in the LDEF orbit. This distribution suggests that the particles come from a source with a steeply falling spectrum outside the magnetosphere. In fact, the strong azimuthal variation in Fig. 4 is in reasonably good numerical agreement with calculations based on Stormer theory. This angular distribution is dramatically different from what would be expected for geomagnetically-trapped particles in the HIIS detectors[7,10,11].

Iron Flux and Spectrum. Fig. 5 shows our mission- and acceptance-averaged Fe flux measurements at the surface of the satellite, after corrections for energy-loss and fragmentation in the detector. Our flux measurements are in good agreement with those from the Kiel[10,11] and Siegen[12] experiments on LDEF.

The galactic cosmic ray curve (GCR) in Fig. 5 is an absolute prediction, averaged over the solar-cycle variation[13] during the LDEF mission and convoluted with the geomagnetic transmission function[14]. The transmission function we used here took into account cutoff suppression due to geomagnetic storms. This transmission function was calculated using (1) Monte Carlo methods[15,16] to randomly sample HIIS lookout directions and locations along the LDEF orbit; and (2) a trajectory-tracing program[17] to determine whether or not a particle of the specified rigidity had access to HIIS from interplanetary space. The trajectory tracing program incorporated both the International Geomagnetic Reference Field (IGRF)[18] to describe the internal magnetic field of the Earth and the Tysganenko model[19] to describe the contributions from currents in the outer magnetosphere. With this program, we calculated transmission functions for 10 different levels of geomagnetic activity,[5*] corresponding to Kp=0-9. These ten transmission functions were then combined in a weighted average, with relative weights determined from a survey of geomagnetic activity during the LDEF mission.

As an independent check on our cutoff suppression analysis, we also repeated the transmission function calculation using the model of Flueckiger, Smart, and Shea[20] (hereafter FSS). The FSS model gives an analytic expression for the cutoff-suppression at mid- and low-latitudes as a function of *Dst*. This model gives a reasonably good description of cutoff supressions at neutron monitor stations which cover the same rigidity range as LDEF.

At the highest energies (> 800 MeV/nucleon), our Fe flux is consistent with GCRs. Both the trajectory tracings and the FSS model, however, indicate that fully-ionized galactic cosmic rays cannot account for the observed flux at lower energies. In particular, both cutoff suppression calculations indicate that even a geomagnetic storm as severe as $Dst = -300$ nT would not allow fully-stripped Fe ions to reach the LDEF orbit at energies below ~500 MeV/nucleon. During the 6-year LDEF mission, there were only 11 hours during which $Dst < -300$ nT. We calculate that the GCR Fe fluence collected during these 11 hours falls at least 3 orders of magnitude below the observed fluence. Moreover, as already shown in Fig. 3, the observed sub-Fe/Fe ratio is also inconsistent with that of GCRs.

Analysis of Fig. 5 has also led us to reject albedo as a possible source of the observed flux. To match the observed flux and spectrum, $\geq 20\%$ of all GCRs would have to pass through ≥ 25 g/cm^2 of atmosphere[21]. Such a large pathlength implies a grazing, nearly-horizontal trajectory through the atmosphere, which seems unreasonable for such a large fraction of the incident GCRs. Also, as already shown in Fig. 3, passage through so much atmosphere before reaching LDEF would yield a much larger sub-Fe/Fe ratio than we observe.

[5*] The Tsyganenko model describes the magnetospheric fields using fits to satellite magnetometer data, with 6 sets of fit parameters corresponding to geomagnetic activity levels of Kp = 0,1,2,3,4, and ≥ 5. The magnetometer data used by Tsyganenko were too sparse to provide separate fits to the model parameters at rare, very high levels of geomagnetic disturbance (Kp=6-9). In order to extend the Tsyganenko model to these very large disturbances, we adjusted one key parameter (denoted c_5, which describes the strength of the ring current) in a way which is consistent both with the observed *Dst* values and studies of cutoff suppression at mid- and low-latitude neutron monitor stations. This extension has been tested by comparing it with the measured geomagnetic transmission of solar energetic protons, as deduced from simultaneous observations on GOES-7 (in geosynchronous orbit) and NOAA-10 (in low-Earth orbit) during the large SEP events and geomagnetic disturbances of October 1989. Details of this extension will be published elsewhere (Boberg et al., in preparation).

To further study solar energetic particles in the HIIS data, we obtained a survey[6*] of SEP events during the LDEF mission from the University of Chicago instrument on IMP-8. Preliminary results from this survey show that only 3 events (beginning on 29 September, 19 October, and 24 October 1989) produced significant Fe fluences above 200 MeV/nuc. The time-profile of these events and the accompanying *Dst* variation are shown in Fig. 6. For these three events, the Chicago instrument provided both Fe fluences at 200-400 MeV/nuc and spectral indices. In terms of high-energy heavy-ions, the 24 October 1989 SEP event was the largest that occurred during the LDEF mission. The 19 October 1989 event also contributed a significant fluence to the LDEF observations because of the large geomagnetic storms and cutoff suppression which accompanied it.

For each of these three SEP events we calculated a separate geomagnetic transmission function. To do this we again used trajectory tracings combined with Monte Carlo samplings of HIIS lookout directions and locations along the LDEF orbit: at each rigidity, the value of the transmission function was given by the fraction of trajectory tracings which successfully tracked back to interplanetary space. But because the SEP events were so dynamic, with interplanetary particle fluxes and (generally) geomagnetic activity levels changing by large factors over relatively short times, some additional factors had to be included in the transmission calculations. In particular, we used the actual LDEF orbital trajectory, as reconstructed from orbital elements obtained from US Space Command. Since *Dst* (the geomagnetic index apparently best correlated with cutoff suppression) is available in hourly averages, we then divided the orbital trajectory into one-hour segments. On each segment, we adjusted the ring-current strength parameter (c_5) in the Tsyganenko model to match the observed *Dst*. Also, the number of samplings attempted on each segment was proportional to the SEP fluence outside the magnetosphere at that time[7*]. This fluence-weighting is an important feature of the calculation, since (for example) it ensures that a large geomagnetic disturbance (and hence high transmission) which occurs when the SEP fluence is small contributes to the transmission function only at the appropriate level.

For each SEP event we thus had a transmission function and a measured fluence and spectral index outside the magnetosphere. We used these to calculate the combined contribution of these three SEP events to the HIIS Fe fluxes. In these calculations, we varied the mean ionic charge state <Q>, which we assumed to be the same in all 3 events and independent of energy. Fig. 5 shows the fluxes we calculated for various <Q> values. Clearly, <Q> ~ 13 - 14 gives a good description of the LDEF measurements above ~200 MeV/nucleon.

There is one additional ingredient in the calculations of Fig. 5 which should be noted here. The calculated spectrum depends not only on the *mean* ionic charge value but also the actual *distribution* of ionic charge states. Low-energy ionic charge state observations are not precise enough to measure this distribution directly, so the distribution must be taken from theoretical calculations about the source plasma. These calculations, which determine the distribution corresponding to a specified plasma temperature (and hence <Q> value), take into account the detailed atomic cross-sections for electron stripping and pick-up. For the curves in Fig. 5, we used the theoretical calculations of Arnaud & Raymond[24]. We also tried the calculations of Shull and Van Steenberg[25], which resulted in slightly different normalizations and spectral shapes.

From the HIIS Fe measurements above 200 MeV/nucleon, we determined the best-fit value <Q> = 13.4 $\pm$ 1.0. The error bar quoted here comprises statistical and systematic uncertainties

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[6*] W.F. Dietrich, 1992, private communication.

[7*] We used several different interplanetary fluence measurements, including protons from GOES-7, alphas from IMP-8, and (after 19 October 1989) heavy ions from Galileo. These fluence measurements were available in different energy intervals and on various time-scales, ranging from 5-minute to 3-hour averages. Using these different fluences to monitor the SEP's temporal evolution gave transmission calculations which generally agreed to within ~10%.

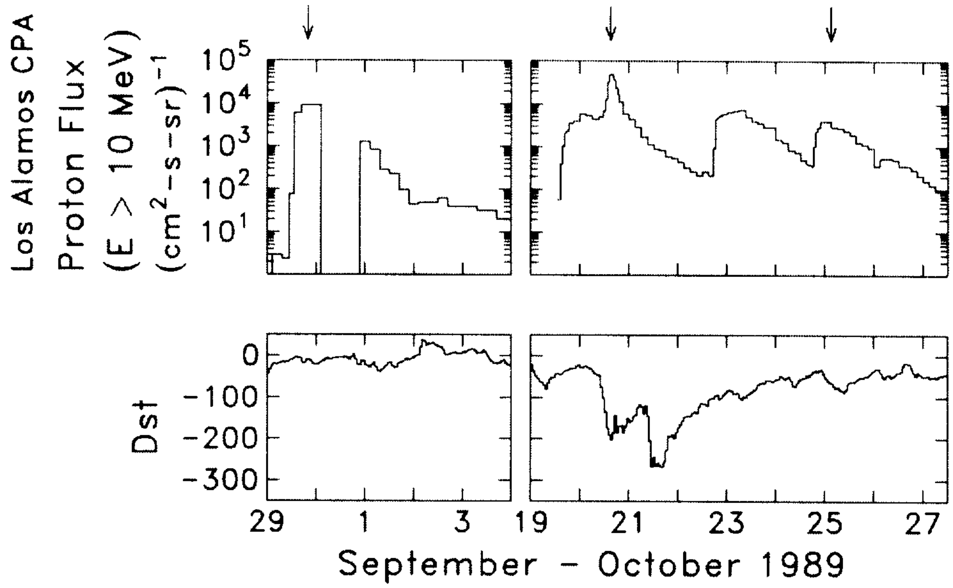

Figure 6: The upper panel shows the time history of the Sept.-Oct. 1989 SEP events, as monitored by >10 MeV proton fluxes from the Los Alamos CPA instrument[22] in geosynchronous orbit. The arrows mark the peaks of the 3 events which produced significant Fe fluence above 200 MeV/nucleon. The lower panel shows the *Dst* history[23] for this same period. There is a gap in the CPA data on 30 Sept. This gap had no impact on our analysis.

including: (1) statistical error in the HIIS measurements (as shown in Fig 5); (2) statistical error in the IMP-8 measurements (provisionally estimated at 20%, pending further analysis); (3) 15% random uncertainty in the transmission calculation (based on comparison of calculated and observed transmission of solar energetic protons in ~60 three-hour intervals during the October 1989 events[8*].) Among sources of systematic error we have considered are (1) 10% systematic error in the HIIS flux measurement, based on track misidentification estimates and uncertainties in calibration and acceptance calculations; (2) systematic uncertainty caused by the choice of either Arnaud & Raymond[24] or Shull & Van Steenberg[25] charge state distributions; and (3) systematic uncertainty in the transmission calculation. In particular, we repeated our transmission calculations using the FSS cutoff suppression model[20]. These results gave a slightly lower best-fit value of <Q> and a somewhat better fit to the observed spectral shape above 200 MeV/nuc. At present, this systematic uncertainty in the transmission calculation is the dominant source of error in our measurement.

There is, however, another potential source of systematic error in our result which we have not yet fully evaluated. This error arises from the possible contribution of additional unidentified sources to our Fe fluxes. Any such additional source will bias our <Q> toward a lower value; an additional source produces excess flux, which falsely implies higher geomagnetic transmission and thus a lower mean charge state. The composition results (Fig. 3) show that, at least on average, albedo does not make a significant contribution to our Fe flux.[9*] Also, the observed arrival direction distribution rules out a significant trapped particle contribution above 200 MeV/nuc. But additional SEP events, which were individually too small to be measured by the IMP-8/Chicago instrument, may contribute to the HIIS flux. Further analysis is required to put quantitative upper limits on the possible contributions of such sources above 200 MeV/nucleon.

[8*] P.R. Boberg et al.: Geomagnetic Transmission During the Solar Energetic Particle Events of October 1989, in preparation.

[9*] Albedo contamination could arise in the Fe spectrum not from fragmentation of heavier ions, but by slowing down in the atmosphere before reaching LDEF.

A striking feature of Fig. 5 is the particle fluxes *below* ~200 MeV/nucleon. Our calculations to date have not been able to explain this data in terms of the SEP fluences and cutoff suppression of October 1989. Also, it is interesting to note that the sub-Fe/Fe ratio in Fig. 3 is somewhat higher than expected at these lower energies. At present, the statistical significance of this sub-Fe excess is only about 2σ, but it may suggest an additional source other than SEPs. Additional composition measurements are critical for understanding the source of these particles.

If the sub-Fe excess is indeed just a statistical fluke, another possibility is that a significant fraction of the fluence below ~200 MeV/nuc may be due to the SEP event of 6-15 March 1989. This event was both smaller and had a steeper spectrum than the events of October 1989. But the largest geomagnetic disturbances of the LDEF mission (including 10 of the 11 hours when $Dst < -300$ nT) occurred during the declining phase of this event. Because of the very large and complex geomagnetic disturbances during this period, modeling the geomagnetic transmission for this event is very challenging. But if this storm did provide access to the LDEF orbit for a significant fluence of SEP Fe ions below 200 MeV/nucleon, it may also be the source of the trapped Fe observed by the Kiel experiment. Such ions could become stripped of their remaining orbital electrons in the residual atmosphere and then become stably-trapped, just as anomalous cosmic rays do. (For further discussion, see Kleis et al[7]. in these Proceedings.)

SIGNIFICANCE OF THE HIIS RESULTS

Origin of Solar Energetic Particle Events. The HIIS results are the first observation of partially-ionized SEPs above ~1 MeV/nucleon. In many analyses[26,27] of SEP data, it has been implicitly assumed that the charge states measured at ~1 MeV/nucleon continue to higher energies. This assumption has been a key ingredient in uncovering patterns of systematic variation in SEP events. The HIIS results therefore validate this otherwise unverified assumption.

The HIIS results show that the mean ionic charge states of SEPs remain essentially unchanged as the particles are accelerated from ambient plasma temperatures up to hundreds of MeV/nucleon. Qualitatively, this observation implies that the acceleration cannot take place in a relatively dense plasma, such as found at the site of a solar flare, in the chromosphere or corona. Our results therefore add another confirmation to the growing consensus[28-31] on the origin of large SEP events in interplanetary shocks driven by coronal mass ejections. Moreover, it should be possible to use the HIIS results to put a stringent upper limit on the amount of matter traversed during the acceleration process and the plasma density in the acceleration region. The high energies investigated here are particularly powerful in such studies, since high energy particles must have longer residence times and hence much longer pathlengths in the acceleration region than low energy particles.

Significance for Radiation Environment Modeling. Partially-ionized heavy ions can penetrate to orbits which are largely shielded from fully-ionized cosmic rays by the Earth's field. This is illustrated in Fig. 7a, which shows the event-averaged integral LET spectrum for the 24 October 1989 SEP event in the LDEF orbit, as deduced from the IMP-8 and HIIS fluence measurements and modeling of the geomagnetic transmission during this period. Note that the spectra are calculated behind 0.25" of aluminum shielding. They are also averaged over all lookout directions and take into account the presence of the solid Earth. The calculation is shown for two different assumptions about the SEP charge state, fully- or partially-ionized. The spectra include all elements[10*] with $Z \leq 28$.

[10*] We used the measured interplanetary fluence and spectra of protons and Fe. For other elements, the Fe spectrum was scaled by the relative abundances given in Ref. 32. In the partially-ionized calculation, we used for these other elements the mean charge states reported in Ref. 3 and the theoretical charge state distributions given in Ref. 25.

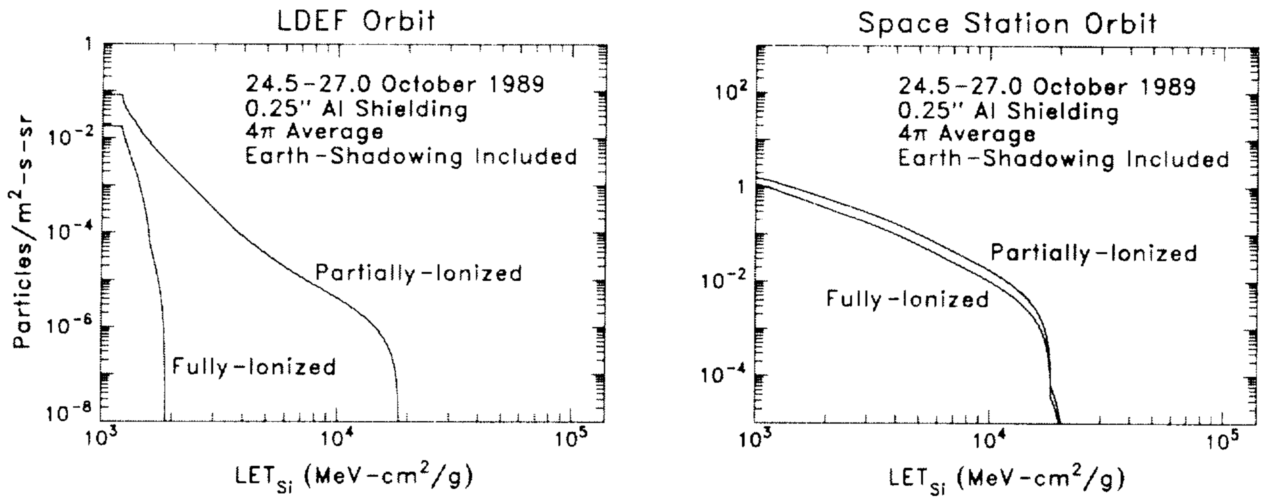

Figure 7: Integral LET spectra in silicon from solar energetic particles, as calculated behind 0.25" of Al shielding, averaged over the period of 24.5-27.0 October 1989. The calculation is shown for two cases, fully- or partially-ionized SEPs. Results are shown in (a) the LDEF orbit and (b) the proposed Space Station orbit. Note the different vertical scales on the two panels. During the peak hour of the event, the flux was larger by roughly an order of magnitude.

It is clear from Fig. 7a that the SEP charge state is an essential ingredient in making a reliable estimate of the radiation hazard posed by this event to systems in the LDEF orbit. Many microelectronic systems start to become vulnerable to upset effects in space at LET ~10^3 MeV-cm^2/g. The partially-ionized SEPs give a flux of particles with LET above this threshold ~5 times higher than fully-ionized SEPs would. At higher LET thresholds, the discrepancy grows by orders of magnitude. At LET ~10^4 MeV-cm^2/g nearly all microelectronic systems become vulnerable. The SEP charge state is therefore crucial in correctly evaluating the reliability of critical systems normally thought to be immune to upset effects in low-inclination orbits.

The single event upset (SEU) rates implied by Fig. 7a are indeed significant. As a specific example, we calculated the SEU rate in a 1-Gbyte solid state recorder which employs the Hitachi 4-Mbit dynamic random access memory (DRAM). Using the methods given in Ref. 33, the partially-ionized LET spectrum in Fig. 7a gave an upset rate of ~ 2 SEU/minute in the 1-Gbyte recorder. This upset rate is sufficiently large that it should be properly taken into account by systems designers.

*These results on the mean-ionic charge state of solar energetic particles are **not** included in widely-used space radiation models such as CREME[34]. As a result, the radiation hazard posed by SEPs in low-inclination, low-altitude orbits may be substantially underestimated by these programs.*

Fig. 7b shows the same calculations, but for the 51.6°, 450 km orbit proposed for the Space Station. Because geomagnetic transmission is generally higher in this orbit, the charge state makes relatively little difference to the estimated radiation hazard. Note that Fig. 7b is based on actual fluence data and a detailed geomagnetic transmission calculation for the SEP event with the single-largest fluence of high-energy heavy ions during the entire LDEF mission. It is therefore useful as a reasonable and realistic estimate of the event-averaged radiation hazard posed by large SEPs to the Space Station orbit.

Finally, another important consideration in assessing the radiation hazard is the arrival directions of the solar energetic particles. The calculations in Fig. 7 are averaged over arrival directions. But, as seen in Fig. 4, the SEP flux is highly anisotropic in a low-inclination orbit, with the flux of the highest-LET particles higher from the west than from the east by a factor of ~100. Consequently, the SEP radiation hazard can be reduced significantly by placing the most vulnerable components on the "eastward-looking" side of an orientation-stabilized satellite. In the proposed Space Station orbit, on the other hand, the orbit-averaged east-west asymmetry would be small.

COMPARISON OF LDEF RESULTS TO PREVIOUS REPORTS OF BELOW-CUTOFF Fe-GROUP IONS

Over the years there have been numerous reports[35-40] of below-cutoff Fe-group ions in the inner magnetosphere. These observations were generally made at times free of SEP events, and the arrival directions and collection locations were inconsistent with trapped particles. Some observations also showed a greatly enhanced sub-Fe/Fe ratio[41,42]. These observations comprised just a few tens of ions, but they have nevertheless stimulated much speculation about partially-ionized *galactic* cosmic rays[43,44], suggesting a nearby source of galactic cosmic rays (such as cosmic rays in the first stages of acceleration after encountering the expanding shock from a relatively nearby and recent supernova.)

All of these other experiments were at higher inclinations (ranging from 51.6° - 82°) than LDEF. But most also had some timing information, using either an electronic detector[39] or moving stacks of track detectors[35-38]. In these experiments, it is therefore possible to identify the small subsample of the ions which were collected within ±28.4° latitude. After accounting for the observation time actually spent at these latitudes, the resulting fluxes can be compared to the mission-averaged fluxes on LDEF.

Fig. 8 shows a compilation of all Fe and Fe-group fluxes reported to date from LDEF, including the trapped Fe-group ions from the Kiel experiment[10,11]. Also shown are the fluxes calculated from the results reported by two experiments,[11*] a rotating track-detector apparatus flown[38] on Spacelab-3 and a stack of ionization chambers[39] flown on Cosmos-2022. Because of the latitude cut, these fluxes are based on just *four* identified Fe-group ions. But these four ions were collected in less than two weeks with instruments with smaller geometry factors than those on LDEF. The LDEF experiments should easily have been able to confirm the flux levels implied by these few events. Instead, these fluxes *exceed* the LDEF mission-averaged fluxes by a large factor, even though the LDEF fluxes also contain both SEPs and trapped ions.

One obvious way to reconcile these other observations with the LDEF results is to posit that these below-cutoff ions were present at the reported flux levels for only a small portion of the LDEF mission. Such an explanation is entirely possible, but it would seem to be highly problematical for the notion of a new galactic component. Fig. 9 shows the time periods of the various observations, compared to the solar cycle, as tracked by the Mt. Washington neutron monitor. Note that the LDEF observations span a solar minimum, when solar modulation is most favorable for particles entering the heliosphere from interstellar space. But the other observations were made during periods of higher solar modulation. This too suggests that if the below-cutoff ions really did originate from outside the solar system, the mission-averaged LDEF flux should have been *higher*, not lower.

Taken together, these previous observations of below-cutoff Fe-group ions are almost surely correct, since different groups using different detector techniques at widely separated times report comparable flux levels. But it seems difficult to reconcile the comparison to LDEF results with the notion of a new galactic component.

One additional point may be worth mentioning here. All of the other observations were made at altitudes of 250-370 km. For most of its 69-month mission, LDEF was at 476 km, but the orbit decayed rapidly in the final year. In the last month of the mission, LDEF's altitude fell to ~370 km, and it was finally retrieved at ~330 km. If below cutoff Fe-group ions were collected by LDEF at the previously

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[11*] Results from two additional experiments are not plotted on Fig. 8. A track detector experiment[35] on Salyut-6 saw a flux level comparable to that shown for Cosmos-2022. But the Salyut-6 detector was exposed *inside* the space station, and the amount of shielding surrounding the apparatus was only poorly known. The energy interval of the observed ions was therefore not well determined, and it is difficult to know where to plot this result on Fig. 8. There is also a report from the Kiel experiment[36] on Spacelab-1, which observed 12 below-cutoff Fe-group ions, but all at high latitudes. From this result we have calculated a 90% C.L. upper limit of $5 \times 10^{-6}/m^2$-s-sr-MeV/nucleon for Fe-group ions with E = 70-140 MeV/nucleon at LDEF latitudes, and thus consistent with the other measurements.

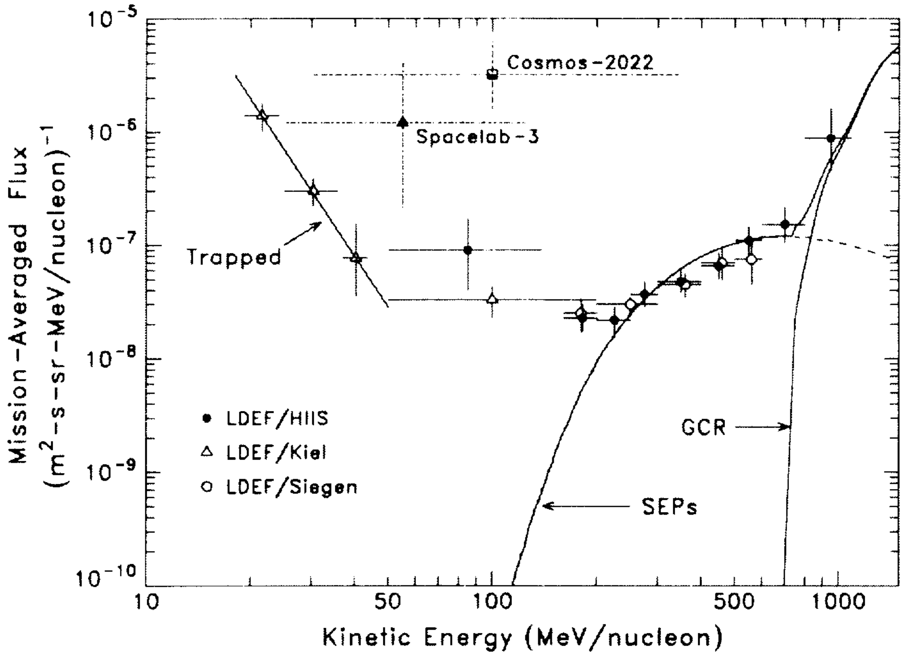

Figure 8: Mission-averaged Fe flux measurements from LDEF. Also shown are fluxes of below-cutoff Fe-group ions observed within ±28.4° latitude by experiments on Spacelab-3 (Ref. 38) and Cosmos-2022 (Ref. 39).

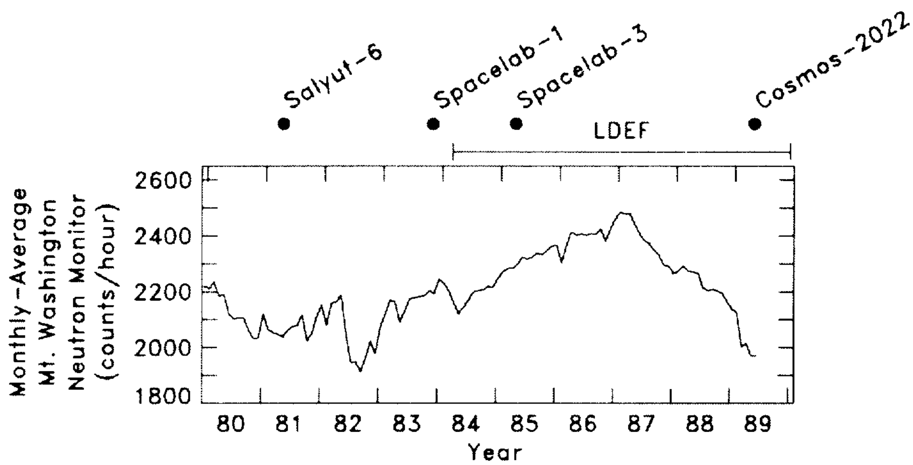

Figure 9: Times of the various observations of below-cutoff Fe-group ions, compared to the solar cycle as shown by the Mt. Washington neutron monitor.

reported flux levels *only during this last month*, the contribution to the *mission-averaged* flux would then be ~3 x 10^{-8}/m^2-s-sr-MeV/nucleon, and hence consistent with the as-of-yet unexplained LDEF flux at ~50-200 MeV/nucleon. But once again, such a steep increase with decreasing altitude seems hard to reconcile with a new galactic component.

In any case, these reports of below-cutoff ions should be confronted soon by new data from the SAMPEX satellite, which has been flying in an 82° orbit at ~600 km since July 1992. If the below-cutoff Fe-group ions are present at the SAMPEX orbit at the flux levels suggested by these earlier observations, the SAMPEX instruments should observe ~100 such ions per year[12*]. If SAMPEX does

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[12*] The MAST instrument on SAMPEX has reported one Z = 23 ion collected at 1.45 < L < 2.65 during the first seven months of operation[45].

not confirm the earlier flux levels, a strong altitude dependence may remain as the only way to reconcile all of the observations. Such an altitude dependence would rule out a new galactic component, but it might be explainable in terms of albedo.

CONCLUSIONS

The HIIS detector has observed a large flux of Fe ions at ~200-600 MeV/nucleon which cannot be explained by fully-ionized galactic cosmic rays, even after taking into account occasional severe cutoff suppressions during the LDEF mission. The observed composition of the Fe-group ions also rules out galactic cosmic rays and albedo as their source. But all of the features of the HIIS data in this energy range, including fluence, spectrum, composition, and arrival directions, can be explained by the large solar energetic particle events of October 1989, provided that these SEP ions are partially-ionized. By comparing the HIIS fluxes with interplanetary measurements in October 1989, we determined the mean ionic charge state of SEP Fe ions to be $\langle Q \rangle = 13.4 \pm 1.0$, in good agreement with the value $\langle Q \rangle = 14.1 \pm 0.2$ measured at ~1 MeV/nucleon.

Thus, even at these very high energies, SEP Fe has a mean ionic charge state very similar to that of the source population in the coronal or solar-wind plasma. The acceleration must therefore take place in a very low-density region, and not at the site of a solar flare. The HIIS result is consistent with the notion of SEP acceleration in interplanetary space by shocks driven by coronal mass ejections. With additional theoretical analysis, it should be possible to use the HIIS result to further characterize the region where the acceleration takes place.

The ionic charge state of high energy SEPs is essential for correctly assessing their radiation effects on systems in low-inclination, low-altitude orbits. *It should be a high-priority of the space-environment modeling community to update widely-used programs such as CREME to reflect this new information.*

The source of Fe-group ions at ~50-200 MeV/nucleon is not yet understood. One possible source is the SEP event of 6-15 March 1989. This event did not produce measurable interplanetary Fe fluences above 200 MeV/nucleon, but it was accompanied by the largest geomagnetic disturbances of the LDEF mission. Another possible contributor in this energy range is the unidentified source of below-cutoff ions reported by several earlier experiments. Since these earlier experiments also reported a substantially enhanced sub-Fe/Fe ratio, better composition measurements will be crucial in unraveling this energy range.

LDEF mission-averaged fluxes are far below the flux levels reported in those other observations of below-cutoff Fe-group ions. This is somewhat surprising since (1) the LDEF fluxes also contain both SEPs and trapped ions; and (2) the LDEF observations span the 1987 solar minimum, while the other observations were all made nearer to solar maximum. To reconcile the LDEF and previous observations, the source of these below-cutoff ions must be out-of-phase with the observed solar-cycle variation of other known non-solar cosmic ray sources and/or strongly increase with decreasing altitude. Both of these features would be hard to understand if the source of these below-cutoff ions really were a new component of partially-ionized galactic cosmic rays.

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