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CHARACTERISTICS OF LOW ENERGY IONS IN THE HEAVY IONS IN SPACE (HIIS) EXPERIMENT

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SUMMARY

We present preliminary data on heavy ions ($Z \geq 10$) detected in the topmost Lexan sheets of the track detector stacks of the Heavy Ions in Space (HIIS) experiment (M0001) on LDEF. The energy interval covered by these observations varies with the element, with (for example) Ne observable at 18–100 MeV/nuc and Fe at 45–200 MeV/nuc. All of the observed ions are at energies far below the geomagnetic cutoff for fully-ionized particles at the LDEF orbit. Above 50 MeV/nuc (where most of our observed particles are Fe), the ions arrive primarily from the direction of lowest geomagnetic cutoff. This suggests that these particles originate outside the magnetosphere from a source with a steeply-falling spectrum and may therefore be associated with solar energetic particle (SEP) events. Below 50 MeV/nuc, the distribution of arrival directions suggests that most of the observed heavy ions are trapped in the Earth's magnetic field. Preliminary analysis, however, shows that these trapped heavy ions have a very surprising composition: they include not only Ne and Ar, which are expected from the trapping of anomalous cosmic rays (ACRs), but also Mg and Si, which are not part of the anomalous component. Our preliminary analysis shows that trapped heavy ions at $12 \leq Z \leq 14$ have a steeply-falling spectrum, similar to that reported by the Kiel experiment^{1,2,3} on LDEF (M0002) for trapped Ar and Fe at $E < 50$ MeV/nuc. The trapped Mg, Si, and Fe may also be associated with SEP events, but the mechanism by which they have appeared so deep in the inner magnetosphere requires further theoretical investigation.

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EXPERIMENT DESCRIPTION

The Heavy Ions In Space (HIIS) experiment was mounted on the space-facing end of LDEF, pointing to the zenith. The detector was divided into 8 modules. In each module, the detector contained a main stack (which consisted mostly of CR-39[†] track detector sheets contained in 1 atm of dry air) and a top stack (consisting of 22 5-mil-thick sheets of Lexan[‡], exposed in vacuum under 57 mg/cm² of shielding. For a detailed description of the HIIS detector see ref. 4.) Results from the main detector stacks are given by Tylka et al.⁵ in these proceedings and in ref. 6. In this paper, we present preliminary results on the lowest-energy heavy ions observed in the HIIS detectors. These data come from several test-etchings of small areas of the top stacks, with each test etching using $\approx 50\text{cm}^2$, or roughly 4% of the area of a single module. With these test etchings we have examined approximately 2.5% of the total area available in the top stacks.

In order to reveal stopping ions lighter than the Fe-group, it was necessary to enhance the sensitivity of the Lexan detectors by exposing them to UV radiation prior to etching. This UV exposure, which was done on a machine specifically built for the HIIS Lexan⁷, enhanced the visible track formation that occurred during the etching process. Typical processing parameters used in the test-etchings were 4 or 8 days UV exposure followed by etching in 6.25N NaOH at 70°C for 12 hours.

In this analysis, we required that the cosmic-ray track be followed back through at least one sheet above the stopping point, so that every track has at least two measurable etch pits. (This excludes almost entirely elements with atomic number $Z < 10$ from this analysis and also causes the acceptance for Ne ($Z=10$) to be significantly smaller than that for the heavier registered ions.) For each track we measured the surface ellipse of every etch pit on an image-processing system and the length of the stopping cone on a high precision microscope. We also measured the average post-etch thickness of each sheet. From these measurements, we determined each ion's arrival direction and the v_t/v_b vs. residual range curve, which reveals the ion's atomic number (Z). (See Adams et al.⁸ for further details.)

RESULTS FROM A PRELIMINARY CALIBRATION

Because of the various environmental stresses suffered by the Lexan detectors during their extended space-exposure, we have used internal calibrations, based on the observed cosmic-ray tracks. These calibrations used data from tracks that are arriving from above (from space) and from below (i.e., through the side of LDEF). The particles from above are of greater interest for the

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

[‡]Lexan is the tradename for bis-phenol A polycarbonate, as sold by General Electric, Pittsfield, MA. The same polycarbonate is also sold under the tradenames of Tuffak and Rodyne-P.

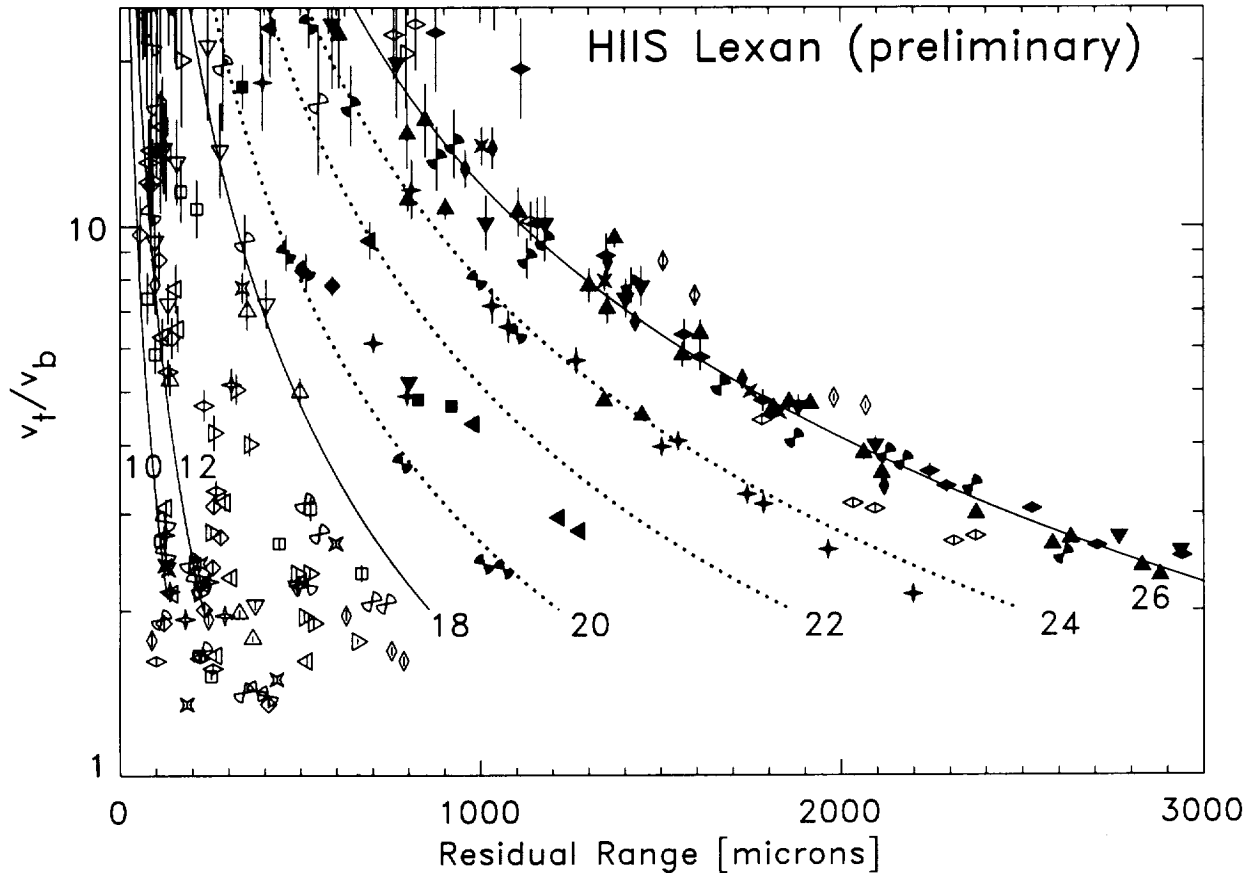


Figure 1: A typical v_t/v_b vs. residual range plot for particles arriving at the HIIS top stack from above (open symbols) and through the side of LDEF (closed symbols). The curves for $Z=26, 18, 12, 10$ (solid) and $Z=24, 22, 20$ (dotted) are derived from an internal calibration. The plot shows track data of 77 particles, registered in $\frac{1}{20}$ module area ($\approx 50\text{cm}^2$). The lightest detected element's nuclear charge is around $Z \approx 10$.

analysis because these are the lowest energy particles observable in the HIIS experiment and because they are well below the LDEF orbit's geomagnetic cutoff for fully-ionized particles.

Figure 1 shows a v_t/v_b vs. residual range plot for particles from $\frac{1}{20}$ module area. It shows a strong accumulation of relatively heavily-ionizing particles, which we assume to be Fe ($Z=26$). Most particles arriving from space, however, have $Z \leq 18$. There are also two visible peaks for very light elements. Using this preliminary calibration, they appear to be Mg ($Z=12$) and Ne ($Z=10$).

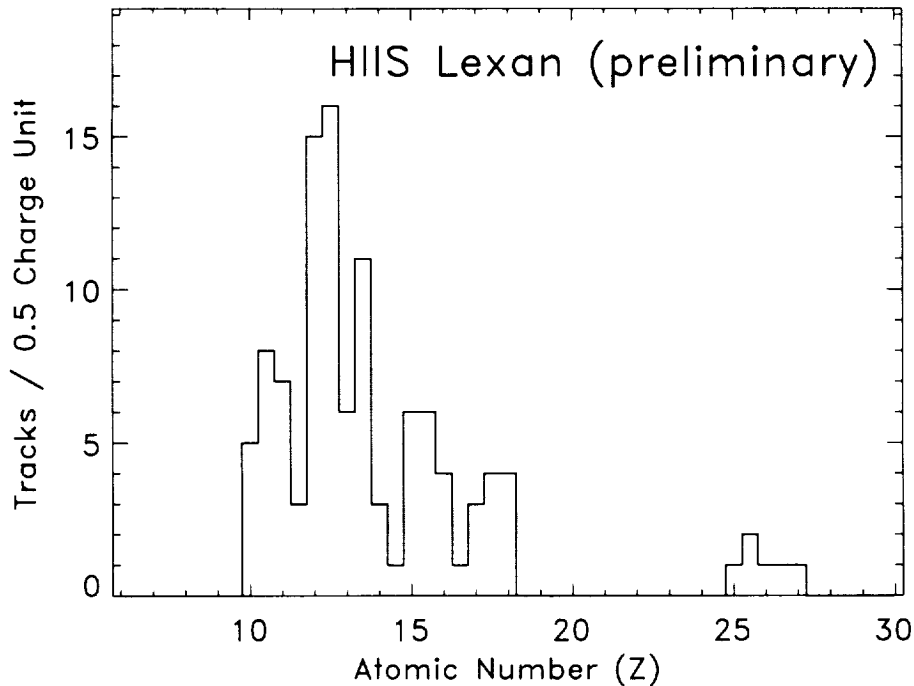


Figure 2: *Preliminary elemental composition of particles registered in the HIIS top stack. The plot includes 109 tracks arriving from space, sampled from test etchings in 2 modules (area $\approx 150\text{cm}^2$). The relative abundances have not been corrected for differences in the acceptance.*

A close examination of figure 1 shows some discrepancies between the data and calibration curves, particularly for the lighter elements at $v_t/v_b \geq 5$. Also, the present calibration curves do not extend below $v_t/v_b = 2$, which is critical for identifying the lighter elements. Certainly the analysis of an entire module instead of $\frac{1}{20}$ module area would greatly increase the statistics and thereby improve the accuracy of the internal calibration.

We have used the preliminary calibrations to examine the elemental composition of the ions arriving from above (fig. 2) from three test etchings of material from two different modules. The accumulation of Fe tracks and the relative absence of sub-Fe ($20 < Z < 26$) tracks is clearly seen. There also appear to be charge peaks at Ne ($Z=10$), Mg (12) and a broad accumulation at $12 < Z \leq 18$. However, given the extended duration of the exposure and complications introduced by partial failure of the HIIS thermal blankets (see Adams et al.⁸), some of this structure may be due to calibration shifts. We emphasize that the composition shown in figure 2 is preliminary. Increased statistics, an improved internal calibration, and comparison with observations of low-energy heavy ions from other LDEF experiments are necessary before any definite conclusions can be drawn about the elemental composition.

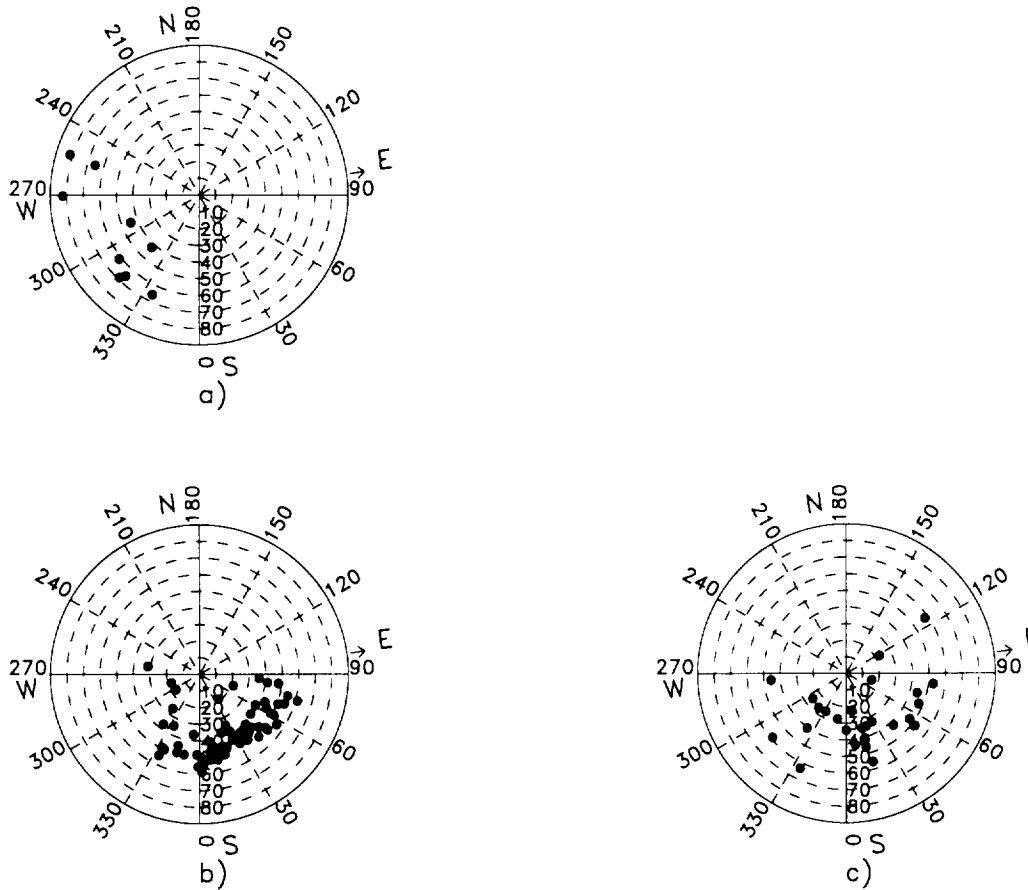


Figure 3: Arrival directions of particles from above in the HIIS top stack. The radial coordinate is the zenith angle, and the azimuth labels (N,S,E,W) apply at the northern and southern extremes of the orbit, when the satellite is moving due east.

a: $20 \leq Z \leq 26$, 9 particles sampled from test etchings in 3 modules (area $\approx 250\text{cm}^2$);

b: $Z \leq 14$, 72 particles sampled from test etchings in 2 modules (area $\approx 150\text{cm}^2$);

c: $15 \leq Z \leq 20$, 27 particles sampled from test etchings in 2 modules (area $\approx 150\text{cm}^2$).

PARTICLE ARRIVAL DIRECTIONS

A close look at the arrival directions allows a classification of particles reaching the HIIS top stack. One group arrives from a broad distribution of directions centered about the southwest. For the larger number of particles, however, the arrival direction lies in a tightly clustered band centered around the southeast. Further analysis shows the particles of the Fe-group ($20 \leq Z \leq 26$) arriving mainly from the southwest (fig. 3a). This is the direction of lowest geomagnetic cutoff, which has been associated with SEPs at $E \geq 200$ MeV/nuc^{5,6}. We point out that this analysis did not detect Fe-group elements below 45 MeV/nuc. The Kiel experiment³ on LDEF has also shown particles in

this elemental range at energies $E \geq 50$ MeV/nuc coming from the southwest.

Particles of the group $Z \leq 14$ are clearly arriving from the southeast (fig. 3b). This band of arrival directions coincides very well with the simulated and measured trapped particle distributions of Jonathal et al.^{1,2,3}. Both experiments see these trapped particles at energies $E \leq 50$ MeV/nuc.

Compared to particles with $Z \leq 14$, the number of particles in the nuclear charge range $15 \leq Z \leq 20$ is much lower. The angular distribution for these particles (fig. 3c) has equal contributions of particles inside the band centered around southeast and of particles from outside that band. Future measurements will increase the statistics of these distributions so that arrival directions can be examined both for different elements and for different energy intervals.

MISSION-AVERAGED SPECTRA AND FLUXES

We have determined preliminary mission-averaged fluxes for Fe and for the group $12 \leq Z \leq 14$. For Fe we observe a mission-averaged flux of

$$J(50 \text{ MeV/nuc} \leq E \leq 140 \text{ MeV/nuc}) \approx 9_{-5}^{+8} \times 10^{-8} [\text{m}^2 \text{ s sr MeV/nuc}]^{-1}.$$

This value is in reasonably good agreement with the Kiel data¹ for $20 \leq Z \leq 26$ ions in this energy range.

For $12 \leq Z \leq 14$ we derive a preliminary spectrum (fig. 4). Although our flux calculation is still very preliminary, our data show a steeply falling spectrum similar to the Kiel data¹ for $14 \leq Z \leq 18$.

The averaged flux for particles $12 \leq Z \leq 14$ is

$$J(25 \text{ MeV/nuc} \leq E \leq 40 \text{ MeV/nuc}) \approx 3 \pm 2 \times 10^{-6} [\text{m}^2 \text{ s sr MeV/nuc}]^{-1}.$$

(Errors given here include statistical and systematic uncertainties, both of which should be reduced by further analysis.)

It should be emphasized that the above flux values are mission-averaged fluxes. That is, the flux has been derived by dividing the fluence collected during the LDEF mission by the total mission time of 5.75 years. We suggest in the next section that the trapped particle fluxes may have substantial temporal variability. In fact, they may be present in the inner magnetosphere only episodically, for days or weeks at a time. If this is indeed the case, then during such periods the actual flux level may be larger by several orders of magnitude. Moreover, the trapped particle flux may also be substantially larger in higher inclination orbits⁹.

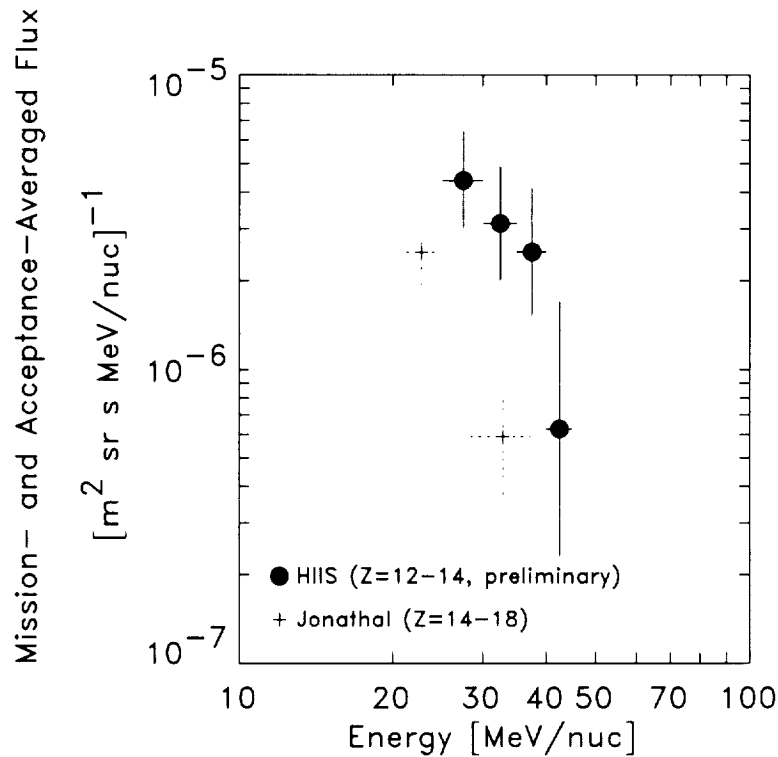


Figure 4: Preliminary energy spectrum of particles $12 \leq Z \leq 14$ compared to data from the Kiel experiment¹ on M0002 for $14 \leq Z \leq 18$.

DISCUSSION

At ~ 50 – 200 MeV/nuc, particles of the Fe-group ($20 \leq Z \leq 26$) appear to arrive from the direction of lowest geomagnetic cutoff. It has been shown by Tylka et al.⁵ that Fe with mean ionic charge state ≈ 14 from the big SEP events of October 1989 can explain the spectrum and fluence of such ions at $E \geq 200$ MeV/nuc. Further calculations to explore the detection of Fe at energies as low as 50 MeV/nuc are under way. In particular, the SEP event¹⁰ which peaked on 13 March 1989 was smaller and had a steeper spectrum, so that it did not produce measurable fluence above 200 MeV/nuc[§]. But during the declining phase of the particle event, Dst reached -589 nT, the largest geomagnetic disturbance of the whole LDEF mission. There may have been sufficient cutoff suppression to account for the particles arriving from the southwest at 50–200 MeV/nuc.

With increased statistics, we will be able to use the observed sub-Fe/Fe ratio to clarify the source of these particles. In particular, solar energetic particles typically have sub-Fe/Fe ratios of a few percent^{11,12}, while galactic cosmic rays and albedo have much larger sub-Fe/Fe ratios (see Tylka et al.⁵).

[§]W.F. Dietrich, 1992, private communication.

More interesting than the Fe ions arriving directly from outside the magnetosphere, however, are the trapped heavy ions suggested in the LDEF data. Most of these trapped species have never been observed before at the relatively high energies considered here.

Anomalous cosmic rays (ACRs) were identified by Blake and Friesen¹³ in 1977 as a potential source of trapped energetic ions in the inner magnetosphere. [For a recent review of trapped ACRs, see Tylka¹⁴.] ACRs are unique among the energetic heavy ions of the interplanetary medium in that they are singly-ionized^{15,16}. Because of this low ionic charge, these ions are able to penetrate deeply into the inner magnetosphere, where the residual atmosphere strips them of their remaining orbital electrons and the ions can become stably trapped. The first conclusive experimental evidence for trapped ACR oxygen was published by Grigorov et al.¹⁷ in 1991, and more recent observations by SAMPEX¹⁸ have confirmed those results. Trapped ACR N and Ne have also been reported^{18,20}. Ar is part of the anomalous component¹⁹, and the results from the Kiel M0002 experiment on LDEF may be the first observation of trapped ACR Ar, since theoretical calculations of the geomagnetic distribution of trapped ACR Ar⁹ agree well with the geomagnetic distribution inferred from the Kiel data¹.

ACRs have a very unusual elemental composition: according to the Fisk, Kozlovsky, & Ramaty model¹⁵ and to all experimental evidence available to date, ACRs originate as neutral atoms in the local interstellar medium (LISM). Consequently, Mg, Si, and Fe, which have low first ionization potentials and are therefore predominantly ionized in the LISM, are *not* expected to be a significant part of the anomalous component.

Mg, Si, and Fe are abundant, however, in solar energetic particle (SEP) events. How such SEP species may become trapped in the inner magnetosphere requires a more elaborate scenario than that outlined by Blake and Friesen for ACRs. In particular, by combining considerations of (1) geomagnetic access and (2) the adiabatic limit of stable trapping, it can be shown [see, for example, Tylka¹⁴] that heavy-ion trapping in the Blake-Friesen mechanism requires:

$$Q/Z < 0.12 - 0.15 \quad (1)$$

where Q and Z are the ion's charge *before* and *after* stripping in the atmosphere, respectively. ACR species (N, O, Ne, Ar) meet this requirement, since $Q=+1$ before stripping. However, SEP Mg, Si, and Fe do not satisfy this requirement: their observed mean ionic charge states in large, so called 'gradual' SEP events are $\langle Q \rangle = 10.8, 11.0, \text{ and } 14.1$, respectively^{21,22} (corresponding to a typical plasma temperature of ~ 2.0 MK in the coronal or solar wind source material). Even taking into account the 'low Q tails' of the charge-state distributions^{23,24} gives $Q/Z > 0.25$ for these SEP species.

In the derivation of equation 1, the requirement for geomagnetic access is stated in terms of cutoffs in a quiet magnetosphere. In fact, closer examination shows that it is this geomagnetic access criterion — and not the limit of stable trapping — which ostensibly precludes solar energetic heavy ions from becoming trapped like anomalous cosmic rays. However, during very large geomagnetic storms which sometimes accompany SEP events, there can be very severe cutoff suppression. This suppression gives solar energetic heavy ions access to regions of the inner magnetosphere which they normally cannot reach. (The SEP event peaking on 13 March 1989 may have been just such an occurrence.) Under such conditions, some of heavy ions could reach the

low-altitude mirror points, be stripped of electrons in the residual atmosphere, and become stably trapped, just as ACRs do in geomagnetically-quiet periods. Moreover, large geomagnetic storms can also promote radial diffusion, which would further energize the trapped particles while transporting them even deeper into the magnetosphere. The LDEF data on trapped Fe (and trapped particles of $12 \leq Z \leq 14$, if further data analysis confirms their existence) may be the first experimental evidence for the geomagnetic trapping of high energy solar heavy ions. But detailed theoretical studies are needed to show exactly how these SEP species actually appeared as trapped heavy ions in the low-inclination LDEF orbit.

Thus, it may be that both anomalous cosmic rays and solar energetic particles contribute to the trapped energetic heavy ions observed aboard LDEF. At the energies observed here, the lifetime of these trapped ions, which is limited by energy loss at encounters with the residual atmosphere at low-altitude mirror points, is expected to be on the order of days to weeks. The composition of trapped energetic heavy ions in the inner magnetosphere should therefore show very interesting temporal variation. ACR species (N, O, Ne, and Ar) should be dominant at solar minimum (which can persist for months or years, depending on the solar cycle), when the ACR source flux outside the Earth's magnetosphere is high. Trapped SEP species (such as Mg, Si, and Fe), on the other hand, should appear much more episodically, after a large solar energetic particle event which was coincident with a large geomagnetic disturbance. Moreover, such events are more common at solar maximum. (The LDEF data are unable to address the question of temporal variability directly, since the LDEF experiments have no timing information on when the ions were collected. According to this scenario, however, the trapped ACR species would have been collected primarily during solar minimum at the first half of 1987. The trapped SEP species, on the other hand, would have been collected during the large SEP events and geomagnetic disturbances of 1989.)

If the trapped particle spectrum for $Z=12-14$ reported in fig. 4 were a permanent feature of the inner magnetosphere at $L \leq 1.8$, it would be detectable by the HILT^{25,26} instrument onboard NASA's SAMPEX satellite at a rate of at least several tens of particles per year. For the same trapped particles the MAST^{25,27} instrument onboard SAMPEX would register roughly a few particles per year.

Finally, we note that there have been several reports of far-below cutoff Fe-group ions with a greatly enhanced sub-Fe/Fe ratio^{28,29,30}. To date, we have no evidence to support these observations, although further analysis on this question is in progress. See Tylka et al.⁵ for further discussion.

CONCLUSIONS

Currently our analysis of the test etchings from the Lexan top stacks shows that HIIS Lexan detects particles $Z \geq 10$ in an energy range $E=20-200$ MeV/nuc inside the earth's magnetosphere. The composition suggests a combination of ACRs and SEPs, with important questions regarding the geomagnetic access of solar energetic heavy ions remaining.

Particles of the Fe group in the energy range $45 \text{ MeV/nuc} \leq E \leq 200 \text{ MeV/nuc}$ are registered mostly coming from the direction of lowest cutoff. These particles may have been collected during SEP events accompanied by very large geomagnetic cutoff suppression. The examination of the sub-Fe/Fe ratio should help to clarify the source of these ions.

For Fe we estimated the mission-averaged flux to be

$$J(50 \text{ MeV/nuc} \leq E \leq 140 \text{ MeV/nuc}) \approx 9_{-5}^{+8} \times 10^{-8} [\text{m}^2 \text{ s sr MeV/nuc}]^{-1}.$$

Particles $Z \leq 14$ at $E \leq 50 \text{ MeV/nuc}$ appear to be trapped in the magnetosphere. For particles with $Z=12-14$ we find a steeply falling spectrum. The preliminary mission-averaged flux is

$$J(25 \text{ MeV/nuc} \leq E \leq 40 \text{ MeV/nuc}) \approx 3 \pm 2 \times 10^{-6} [\text{m}^2 \text{ s sr MeV/nuc}]^{-1}.$$

By etching and measuring one complete module, the statistics of the analysis can be increased at least by an order of magnitude. This should allow a better calibration and enable us to derive the elemental composition and energy spectra. With an improved elemental resolution it should be possible to separate the contributions from anomalous cosmic rays and solar energetic particles.

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