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[9]The differential spectrum of the 709-meV line should then look exactly like the derivative of the normal emission line, and the areas of the corresponding positive and negative bumps shown in Fig. 2(a) should be equal. Even if we take into account the contribution of the 705-meV line, there is still a small difference between these areas which can be explained by a change in the bulk density.

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Composition and Energy Spectra of Heavy Nuclei of Unknown Origin Detected on Skylab*

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(Received 24 March 1975)

At the orbit of Skylab we observed steeply falling energy spectra of nuclei with $Z \geq 8$ and $10 \lesssim E \lesssim 40$ MeV/amu at intensities much higher than seen outside the magnetosphere. The composition is O:Ne:[Na-Si]:Fe = 100:33:13:(~2), consistent with that of the solar corona. We suggest that heavy solar-wind ions enter the magnetosphere, are accelerated, and populate the inner radiation belt.

Lexan track detectors with large collecting power were exposed both outside and inside the Skylab during late 1973 and early 1974. The earth's field excludes from direct access to the Skylab orbit (inclination 52°, altitude 420 km) most particles of energy less than a few hundred MeV/amu that originate outside the magnetosphere. We were therefore surprised to discover a high density of tracks of nuclei with $Z \gtrsim 8$ in the Lexan, indicating a novel source of charged particles with a steep energy spectrum and roughly solar composition, at the orbit of Skylab.

The external detector consisted of a 180-cm^2 stack of 32 sheets of Lexan, total thickness 1 g/cm^2, wrapped in thin aluminum tape, and clamped to part of the Apollo telescope mount with its plane parallel to the sun direction, so as to minimize heating. Both sides were exposed to space from 22 November 1973 to 3 February 1974. To study particles with energy greater than ~100 MeV/amu, we examined one of 35 Lexan stacks exposed from 29 May 1973 to 5 February 1974 inside the Skylab (primarily intended for the study of ultraheavy cosmic rays).

Lexan exposed to the ultrahigh vacuum of space has a weaker response to charged particles than does Lexan exposed in a partial pressure of oxygen. To amplify this weak response, we processed the Lexan in four stages, first by a short irradiation with uv light of ~3100 Å, then by an etch in 6.25N NaOH at 40°C, then by a long irradiation with the same uv light, then by an additional etch in NaOH. Each resulting etch pit has a "shoulder" that permitted both ionization rate and total range to be inferred from its shape and dimensions.[1]

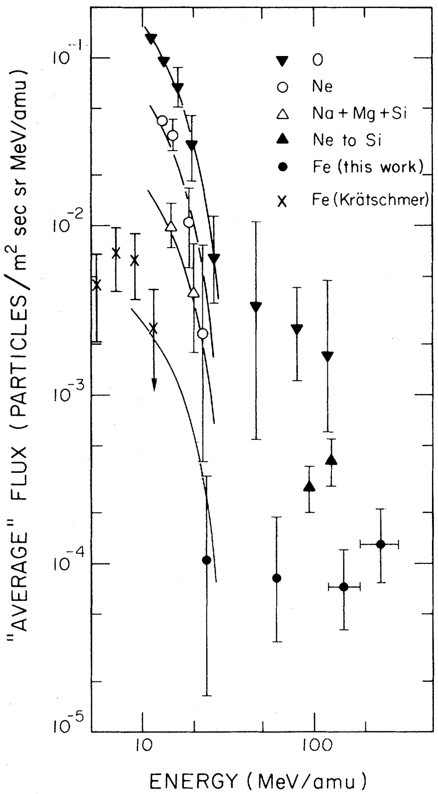

FIG. 1. Energy spectra of the more abundant nuclei with $Z \geq 8$ detected at 420 km along a 52° orbit on Skylab. "Average" flux assumes uniform arrival rate over the entire exposure time. The low-energy Fe data labeled × are unpublished observations by W. Krätschmer of etch pits in glass detectors exposed outside Skylab without any Al cover.

We achieved an internal calibration at low Z by analyzing α-particle tracks from a preflight irradiation and at high Z by calling the heaviest group of particles iron.

We found a high background of short tracks ($\lesssim 10$ μm long) in each sheet, both outside and inside the Skylab. We attribute them to recoil nuclei from spallation reactions of energetic protons from the trapped radiation with carbon and oxygen nuclei in the Lexan.[2] Their high density made it hard for us to study the primary nuclei with $Z \leq 7$ that impinged on Skylab.

Figure 1 shows our analysis of the particles with $Z \geq 8$. The background of recoil nuclei is absent. At energies below ~30 MeV/amu the spectra of the various species are similar and fall steeply with energy. At energies greater than ~100 MeV/amu the spectra (observed in the detector from inside Skylab) begin to rise. Table I gives the composition at energies of ~10 to 20 MeV/amu compared with the composition of the solar corona, of the solar wind, of solar flare particles, of low-energy galactic cosmic rays, and of the ionosphere.

The composition of these particles is so unlike that of the ionosphere (column 7, Table I) that they must certainly have originated from extraterrestrial sources. We consider four possibilities: (1) solar-flare particles; (2) low-energy cosmic rays observed during solar quiet times; (3) the recently discovered anomalous component of low-energy cosmic rays, rich in nitrogen and oxygen; and (4) hitherto undiscovered particles trapped in the inner Van Allen belt.

Fortunately, during the time of our Skylab experiment the California Institute of Technology low-energy electronic detector on IMP-7 was measuring fluxes of heavy particles of energy ~10 to ~30 MeV/amu *outside the magnetosphere.* From these measurements,[8] supplied to us by Stone, together with others[9-11] made since 1972, we make the following assessment of the relative contributions of the four sources:

(1) No strong flux increases indicative of solar flares were recorded on IMP-7 during our experiment. No solar particles were detected.

TABLE I. Relative abundances of heavy elements.

Z	Abundance on Skylab ($E \approx 15$ MeV/amu)	Solar corona [a]	Solar wind [c]	Solar flare particles [d]	Galactic cosmic rays [e] (~20–60 MeV/amu)	Earth's ionosphere [f] (400–1000 km)
O	≡100	≡100	≡100	≡100	≡100	≡100
Ne	33 ± 12	10 [a] to 30 [b]	~20	12 ± 2	18 ± 6	≪1
Na to Si	13 ± 5	15^{+10}_{-6}	>11	27 ± 4	45 ± 9	≪1
Fe	1 to 3.4	5 ± 1	9	8 ± 2	7 ± 3	≪1

[a] See Ref. 3.
[b] See Ref. 4.
[c] See Ref. 21.
[d] See Ref. 5.
[e] See Ref. 6.
[f] See Ref. 7.

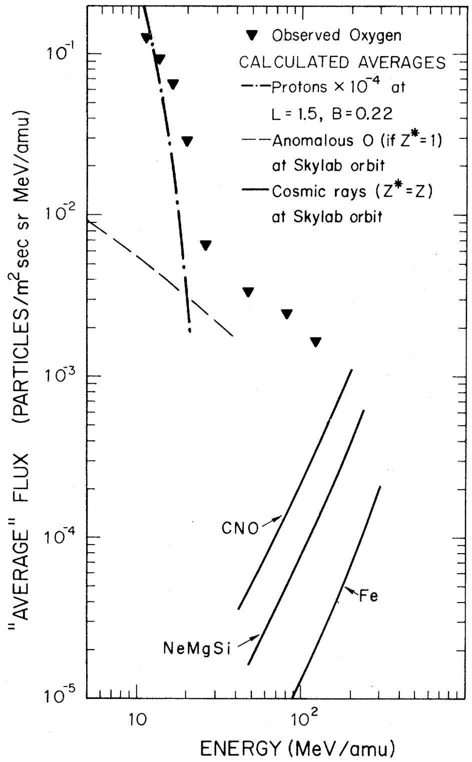

FIG. 2. Possible sources of energetic particles at Skylab orbit (see text).

(2) Galactic cosmic rays can account for our fluxes only at energies greater than ~100 MeV/amu. In Fig. 2 the solid curves are our estimates of the "average flux" of fully stripped cosmic rays that would be seen along the Skylab orbit. They were calculated by correcting cosmic-ray energy spectra outside the magnetosphere for the rigidity-dependent fractional time of access to Skylab orbits, using the grid of vertical cutoff rigidities computed by Shea, Smart, and McCall.[12] As the energy decreases below 100 MeV/amu, our observed fluxes diverge spectacularly from the calculated cosmic-ray fluxes, quite aside from the fact that the composition (column 6, Table I) appears wrong.

(3) Since 1972 an anomalously high flux of oxygen and nitrogen (relative to carbon, for example) has been observed in interplanetary space at energies of ~2 to ~30 MeV/amu (Refs. 8–11). Its origin is unknown, but in one model[13] the charge state is predicted to be only +1. Such particles would have much higher magnetic rigidity than fully stripped nuclei of the same MeV per atomic mass unit, and their fractional transmission to Skylab orbits would be high. The dashed line in Fig. 2 is our estimate of a lower limit for the average oxygen flux at Skylab assuming $A/Z^* = 16$, using the energy spectra from Refs. 9 and 10 and the cutoffs of Ref. 12. Inclusion of the effects of magnetospheric currents would lower these cutoffs appreciably at high latitudes and raise the dashed line. Even with total transmission, our oxygen flux would exceed the anomalous oxygen flux at energies below ~25 MeV/amu.

(4) At energies less than ~30 MeV/amu we interpret our steep spectra as evidence for energetic heavy nuclei in the inner radiation belt. The geographic and energy distribution of trapped protons are reasonably well known.[14] They extend down to altitudes as low as 420 km only at the South Atlantic anomaly, where $L \approx 1.3$ to 1.5, $B \approx 0.22$. The Skylab spent about 1% of its time in this region, where it could detect trapped particles. In comparing actual fluxes of protons in the inner belt with our "average" fluxes, we divide the former by ~100. In Fig. 2 the dot-dashed curve is a portion of the proton spectrum below 30 MeV/amu at $L = 1.5$, $B = 0.22$, divided by 100, and further scaled down by a factor 10^4 chosen so that it overlaps our oxygen spectrum. It is becoming accepted now that at energies above ~25 MeV/amu the ions in the trapped radiation consist mainly of protons from decay of comic-ray–produced neutrons (CRAND),[15] whereas the much more intense fluxes at lower energies originate in the solar wind and are accelerated as they diffuse across L shells into the inner belt.[16]

Our energy spectra in Fig. 1 are suggestively similar in shape to the spectrum of trapped inner-belt protons. The O/p abundance ratio of $\sim 10^{-4}$ at ~10 MeV/amu is uncomfortably high, but the more relevant number, the ratio summed over all energies, may be much lower.

The source of the heavy particles that we claim populate the inner radiation belt is most likely the solar wind. The composition of our particles is similar to that of the solar corona (column 3, Table I), the source of the solar wind. When compared with a recent estimate[17] of solar-wind composition (column 4, Table I), it appears depleted in Fe, but we stress that direct measurements of solar-wind composition are rare and difficult, and indicate strong temporal variability, so that comparison with coronal data may be more significant.

We assume that a small fraction of the solar wind diffuses through the magnetopause either on the sunward side or along the magnetotail.[18] We require the energy per particle to be increased to at least 10 MeV/amu from an initial energy that may be as low as 1 keV/amu, or at best may be a nonthermal tail extending to perhaps 10 keV/amu. Almost a factor 10^3 can be gained by trans-L diffusion from the magnetopause at $L \gtrsim 10$ to $L \approx 1.4$. Higher energies could be achieved by invoking convection of particles from the tail into the outer magnetosphere before diffusion takes place. CNO-group particles with energies up to ~150 keV/amu have recently been detected in the magnetotail and magnetosheath.[19] Trans-L diffusion of these particles could easily lead to energies of tens of MeV per atomic mass unit at $L = 1.4$. CNO-group nuclei have also been detected in the outer zone ($L \gtrsim 3$), both at low energy (0.3 to 1.4 MeV/amu)[20] and at higher energy (13 to 33 MeV/amu).[21] We do not know whether those heavy particles in the outer zone are related to the ones we detected on Skylab.

We conclude that our results support the usual but unproven assumption that most of the energetic particles in the magnetosphere originate in the solar wind.

We are indebted to Nancy Peery-Hutcheon, Edward K. Shirk, Edward C. Stone, and the Skylab astronauts for assistance, and to W. Krätschmer for communicating his results for low-energy Fe nuclei to us before publication.

*Research supported by the National Aeronautical and Space Administration under Contract No. NAS 8-29603.

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