Enhanced Emission of Iron Nuclei in Solar Flares

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Etched tracks in an Apollo-12 spacecraft window and a Surveyor-3 camera-lens filter give the interplanetary Fe energy spectra from ~1 to ~30 MeV/nucleon during 1967-1969. The strongly energy-dependent Fe/He ratio suggests that heavy nuclei are preferentially emitted from accelerating regions because of their low ionization state and high magnetic rigidity. The Fe fluxes give rise to extremely high track densities that we have observed in lunar soil.

From an analysis of tracks in a window of the Apollo-12 spacecraft and in a glass filter from the Surveyor-3 camera brought back from the moon, we have determined the spectrum of Fe nuclei from ~1 to ~30 MeV/nucleon in interplanetary space during the interval 24 April 1967 to 24 November 1969 and in the last 10 days of this interval. The intensity and spectral slope were higher than we expected on the basis of studies of α particles by other investigators[1,2] during that period and the assumption of an Fe/He ratio equal to that in the solar photosphere.[3-5] In addition to their relevance for solar physics, our results may have important consequences for galactic cosmic-ray processes. They also contribute importantly to the extremely high track densities we have observed in the lunar soil[6] and allow us to estimate the rate of erosion of lunar rocks.

The silica glass windows on the Apollo-12 command module were exposed to space with an effective recording solid angle of ~1 sr from 14 to 24 November 1969. A neutral-density flint glass filter over the lens system on the Surveyor-3 camera had an ~0.7-sr effective view of space during a 2.5-yr period while it resided on the lunar surface.

We received one Apollo-12 window and a small piece of the Surveyor camera filter for study. In both types of glass, tracks of heavily ionizing particles can be revealed by chemical etching.[7,8] The visibility of etched tracks depends on ionization rate and increases rapidly with atomic number. From bombardments of glasses with heavy ions we conclude that ions with $Z \leq 16$ record with very low efficiency and leave tracks which etch into pits with a very low visibility when viewed in an optical microscope. For this reason, and since the solar abundance of ions with >16 is strongly peaked at Fe, glass detectors discriminate strongly in favor of Fe. Ions of Fe with energy below ~6 MeV/nucleon, i.e., a range less than ~40 μm, have a sufficiently high ionization rate that they will leave tracks that can be etched into easily recognizable conical pits. Ions of Fe of higher energy have too low an ionization rate to leave etchable tracks at the surface, but the lower energy portions of their trajectories can be exposed by grinding or chemically etching away some of the glass, and these portions can then be detected by additional etching. The depth in the glass at which an Fe track is recorded is thus a measure of its energy.

By means of a sequence of etching (with dilute HF) and grinding operations, densities of etch pits were measured throughout the entire 3-mm Surveyor glass thickness, corresponding to Fe energies from ~1 to ~100 MeV/nucleon, and at the top surface of the Apollo-12 window. Figure 1 summarizes the measurements. In the same figure is shown the etch-pit distribution we would expect if Fe and He were emitted from the sun in the ratio of their photospheric abundances. That distribution was calculated using the α-particle energy spectrum measured during the same 2.5-yr period by solid state detectors on IMP 4 and 5 by Lanzerotti[1] and by Hsieh and Simpson.[2] Seven major solar flares contributed most of the flux. The α-particle spectrum scaled down by the recently redetermined[3-5] solar ratio $(\mathrm{Fe/He})_\odot \approx 2\times10^{-4}$ was used as the input for the calculation.

The large difference between the observed and predicted track densities was completely unexpected. After converting the observed track density distribution to a rigidity (or energy) distribution, we obtain the important result that at low rigidity (or energy) the solar-particle Fe/He ratio is much higher than the photospheric abundance ratio but decreases with increasing rigidity until it approaches the photospheric value at a rigidity of ~500 MV (~25 MeV/nucleon for Fe). In the only previous observations of solar particles with $Z > 20$, Bertsch, Fichtel, and Keames[9] found 23 tracks of Fe-group nuclei in nuclear emulsions exposed in a 5-min rocket flight dur-

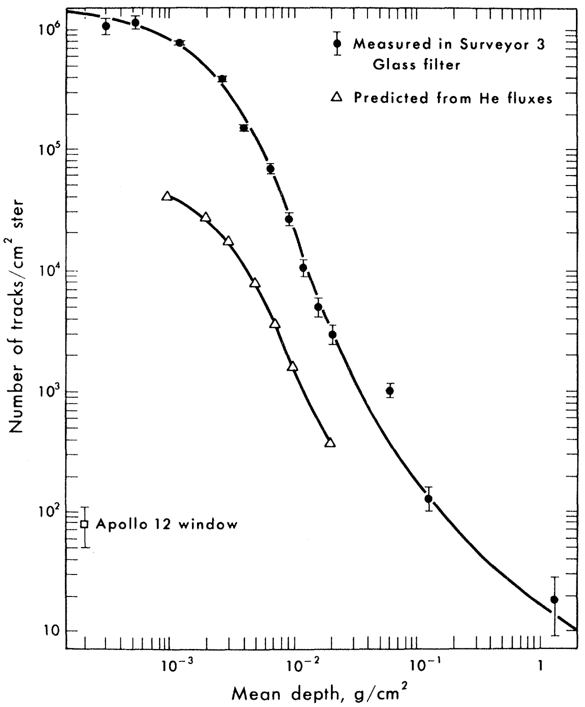

FIG. 1. Observed densities of Fe tracks penetrating to a given depth of Surveyor-3 glass and Apollo-12 glass compared with densities predicted assuming Fe/He solar particle ratio is the same as the photospheric ratio. The tracks are made visible by chemical etching if their residual range at a glass surface is less than ~40 μm.

ing the flare of 2 September 1966. They found $\mathrm{Fe/He} \approx 2\times10^{-4}$ at $E > 24.5$ MeV/nucleon, which is not inconsistent with our results. However, one should keep in mind the possibility that over a 2.5-yr period there may be a significant contribution by galactic cosmic rays with a much higher Fe/He ratio at energies beyond ~25 MeV/nucleon.

During the period 14 to 24 November 1969, in which the Apollo-12 windows were exposed, a small interplanetary enhancement occurred, contributing a flux of α particles only $\sim10^{-4}$ times the total contribution over the previous 2.5-yr period (Lanzerotti[10]). The track counts corresponding to very low-energy Fe nuclei in the Apollo-12 window indicate that the low-energy Fe flux during those 10 days was $\sim7\times10^{-5}$ times the total over 2.5 yrs, in good agreement with the relative α-particle contribution. This result supports the assertion that the low-energy Fe tracks are of solar origin and are not simply an accumulated background of low-energy galactic Fe nuclei.

Our results represent the first evidence that heavy nuclei can be preferentially emitted from a source of energetic particles. Previously Fichtel and co-workers[11,12] had found such a striking similarity between the abundances of energetic solar particles and of the photosphere that the earlier suggestion by Korchak and Syrovatskii[13] that heavy nuclei may be preferentially accelerated has largely been forgotten. Admittedly their mechanism, which applies when the acceleration rate is small, does not account for the strong enhancement of Fe observed by us because acceleration of particles in solar flares takes place so rapidly that the energy loss suffered through ionization by the ions during the acceleration phase is negligible. Instead, we attribute the enhancement to preferential leakage of incompletely ionized heavy nuclei from the accelerating region.

The effective charge of an ion depends on its velocity as $Z^* = Z[1-\exp(-125\beta/Z^{2/3})]$. From this it can be seen that H and He are completely stripped of their electrons even at an energy of ~1 MeV/nucleon, whereas Fe ions have an effective charge of only ~13 at 1 MeV/nucleon, increasing to ~24 at 15 MeV/nucleon and becoming very nearly equal to the nuclear charge, 26, only at energies above ~40 MeV/nucleon. Thus, heavy ions have rigidities higher by a factor $\sim Z^*/Z$ than that of an α particle at the same energy per nucleon.

Now, if the probability of escape of the accelerated particles is a strong function of their rigidity, one can understand the enhanced Fe fluxes. It appears reasonable that heavy ions, which have a higher rigidity because of their smaller effective charge, should leak out preferentially from the flare regions relative to α particles and protons of the same energy per nucleon. This preferential escape, which is a consequence of retention of some electrons around a heavy nucleus, should vanish at those high energies at which all the nuclei of interest are completely ionized. All previous observations[9,11,12] of solar-particle composition have been made at sufficiently high energies that no enhancement would be expected. It is interesting to speculate on the possibility, as previously suggested by Davis,[14] that this process of enhancement of heavy nuclei may operate as the injection mechanism for the galactic cosmic rays which are later accelerated to high energies. Thus the overabundance of heavy nuclei in the cosmic rays may not be entirely indicative of source composition but may be partly a consequence of preferential leakage from the source.

It should also be interesting to solar-particle physicists to mention that the solar α-particle and proton intensities summed over the 2.5-yr period, when plotted as differential rigidity spectra, have the form $\sim A_i \exp(-R/R_0)$, with the same value of R_0 for protons and α particles. Their relative intensities, A_i, scale by a factor ~2, consistent with model calculations of their photospheric abundance ratio. This agreement is consistent with our model of the enhanced Fe emission because both H and He should be completely stripped at energies above ~1 MeV/nucleon.

Turning now to some quite different implications of our results, we can use the track-density measurements in Fig. 1 to draw interesting conclusions about events in the distant past, assumming that the average level of solar activity has remained roughly constant over geologic time:

(1) Rocks exposed undisturbed on the lunar surface for 10^7 years would accumulate about 6×10^{12} tracks/cm in the top 10 μm of their thickness. Accelerator bombardments of certain minerals with neon and argon ions[15] show that extensive strains and fractures occur at track densities $\sim10^{12}/\mathrm{cm}^2$. Summing the contributions of all solar particles with $Z \gtrsim 10$, we conclude that the rate of radiation-induced erosion by fracturing of surface grains is likely to be $\sim10^{-9}$ cm/yr. In current unpublished electron microscope studies of Fe track densities as a function of depth in rocks exposed on the lunar surface for $\sim10^7$ yr, we find a maximum track density of $\sim10^{10}/\mathrm{cm}^2$ at the very surface. The difference between the observed gradient of track density and the gradient to be expected from Fig. 1 is attributed to various erosion processes including atomic sputtering by solar wind ions, cratering by micrometeorite bombardment, and flaking of radiation-damaged grains. We conclude that the total erosion rate of rocks that survive for $\sim10^7$ yr on the lunar surface is $\sim3\times10^{-8}$ cm/yr. This limit agrees very well with the present estimated erosion rate by micrometeorites, $(1\text{-}2)\times10^{-8}$ cm/yr,[15] and allows us further to conclude that the present micrometeorite flux measured now on satellite detectors is nearly the same as the long-term average value.

(2) The lunar soil should contain heavily irradiated small grains, some with track densities of $\sim10^{12}/\mathrm{cm}^2$ that have flaked off of radiation-damaged rock surfaces and some that were irradiated while residing at the top of the soil layer. Given a soil of depth ~5 m that has accumulated over $\sim3.5\times10^9$ yr and has been frequently stirred by meteoritic impacts, we expect an average track density of $\sim10^{10}/\mathrm{cm}^2$ in grains of diameter less than about 10^{-3} cm. Because of the steepness of the solar Fe energy spectrum, larger grains should show visible gradients. We have previously reported all of these features,[6] but were unable to account satisfactorily for the extremely high track densities without knowing the solar-flare Fe spectrum. The steep track density gradient in Fig. 1 now provides a reasonable, quantitative explanation for the bulk of the observations.

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Cosmic Background Radiation at $\lambda = 3.3$ mm

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Ground based measurements of the cosmic background radiation at $\lambda = 3.3$ mm were made at two high-altitude sites. A weighted average of the two measurements corresponds to a blackbody temperature of 2.61 ± 0.25 K.

One of the main predictions of the primeval fireball model is that the cosmic background radiation has a blackbody spectrum.[1] Previous results obtained at wavelengths $\lambda > 0.856$ cm are consistent with a 2.7-K blackbody.[2] These measurements, however, were in the spectral range where intensity is proportional to λ^{-2} and do not conclusively show the quantum effect which would result in a peak at $\lambda \approx 1.9$ mm. Boynton, Stokes, and Wilkinson (BSW)[3] reported 3.3-mm results which were consistent with a 2.7-K thermodynamic temperature and were the first radiometric measurements to show a clear deviation from the λ^{-2} dependence. This conclusion, however, might be questioned because of their limited amount of data. Indirect measurements at 2.63 mm made by Bartolot, Clauser, and Thaddeus[4] of the absorption lines of interstellar CN indicate further agreement with the postulated spectrum. In contrast Shivanandan, Houck, and Harwit[5,6] and Muehlner and Weiss[7] reported much higher intensities near $\lambda = 1.0$ mm than is expected from a 2.7-K blackbody. Because of its important cosmogonical implications a more precise knowledge of the spectral distribution of the background radiation in the millimeter-wave range is needed. Our laboratories have developed techniques of measurement in this region which we are applying to the investigation of the possible maximum in the radiation curve. In this Letter we describe an independent, ground-based measurement of the radiation intensity at 3.3 mm which yields additional evidence for the deviations from the λ^{-2} dependence appropriate to a 2.7-K blackbody.

Thirty-five background measurements were made at two high-altitude sites in California to minimize seasonal and topographical effects. High, dry sites were chosen to reduce the interfering effects of atmospheric emission. The initial nineteen measurements were performed at the Crooked Creek Station (elevation 10 160 ft, 37°30'N lat, 118°10'W longitude) of the White Mountain Research Laboratory during October, 1969. The final sixteen measurements were obtained near Cerro Gordo on the summit of Buena Vista (elevation 9120 ft, 36°32'N lat, 117°47'W longitude) in the Inyo Mountains during late April and early May, 1970.

The experimental technique was similar to that of Wilkinson[8] as indicated schematically in Fig. 1. A measurement was initiated by referencing the radiometer to an ambient temperature absorber

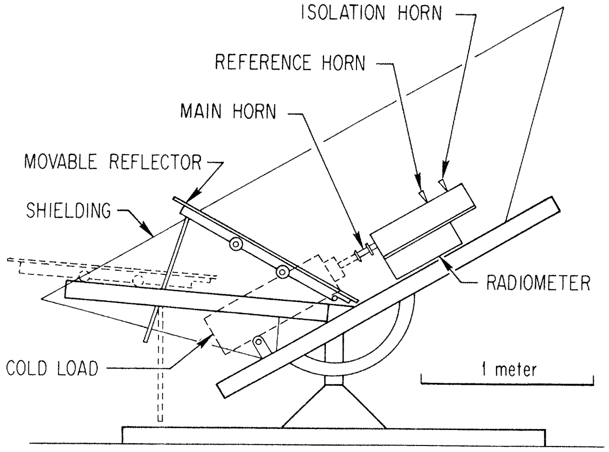

FIG. 1. Apparatus schematic showing the radiometer in the reference position. In this position the zenith sky temperature is compared to the liquid-helium-cooled antenna termination. The apparatus may be tilted so that the main horn points 20° above the horizontal to enlarge the sky-scan angle.