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IN EXTRATERRESTRIAL MATTER: WHAT THEY TELL US
ABOUT RADIATION BACKGROUNDS IN SPACE.

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PRODUCTS FROM COSMIC-RAY INTERACTIONS IN EXTRATERRESTRIAL MATTER: WHAT THEY TELL US ABOUT RADIATION BACKGROUNDS IN SPACE*

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ABSTRACT

The nuclides and the heavy-nuclei "tracks" made by the interactions of solar and galactic cosmic-ray particles with meteorites, lunar samples, and the Earth have been extensively studied, simulated, and modelled. Most research involves the use of these cosmogenic products to study the history of the "targets" or of the cosmic rays. However, much work has also been done in understanding these interactions and in predicting their rates as a function of the target's size and shape and of the location inside the target. These studies apply to any object exposed to cosmic rays. The fluxes as a function of depth for cosmic-ray primary and secondary particles vary greatly with particle energy and type. The variations of the fluxes of these cosmic rays in the past have been studied. Energetic solar particles are unpredictable and are the greatest potential radiation hazard in space.

INTRODUCTION

A wide variety of "cosmogenic" products from cosmic-ray interactions have been measured in lunar samples and meteorites. These products include radiation damage tracks (produced in certain minerals by nuclei with $Z \geq 20$) and rare nuclides that are made by spallation or neutron-capture reactions.[1,2] They are usually used to study the history of the "target" (such as the time period that it was exposed to cosmic-ray particles), but they often have been used to determine the fluxes and composition of cosmic-ray particles in the past.[1,2] These products can also be used to investigate the nature of cosmic-ray interactions with matter in space, complementing studies of the interactions of high-energy particles with matter done at accelerators[3] or with theoretical models.[4-8] Products made by both the high-energy (~GeV) galactic cosmic rays and the energetic (~ 1–100 MeV) particles emitted from the Sun have been extensively studied in meteorites and lunar samples.[1,2] Studies of cosmogenic products in natural extraterrestrial matter can usually be directly applied to spacecraft and other artificial materials in space, especially far from the Earth.

COSMIC-RAY PARTICLES AND THEIR INTERACTION PRODUCTS

The major particles in space that have been studied in extraterrestrial matter are the galactic cosmic rays (GCR), energetic (~1 to >100 MeV) particles from the Sun (hereafter called solar cosmic rays, SCR), and the solar wind. The low-energy ions in the solar wind have been observed implanted in the outer ~50 nm of lunar samples. As the solar wind contributes very little to radiation

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backgrounds in space, it won't be discussed any further here. The nature of the galactic and solar cosmic rays and their interactions will be discussed in detail. The galactic cosmic rays have fairly low fluxes ≈ 3 cm^{-2} s^{-1} and high energies ($\sim$ GeV) whereas the particles emitted by solar flares have high fluxes (up to $\sim 10^6$ cm^{-2} s^{-1} at the peak of an event and a long-term average flux of $\sim$100 cm^{-2} s^{-1}) with fairly low energies (mostly $\sim$1–100 MeV).[1,2,4,5,9,10] A summary of the energies, mean fluxes, and interaction depths in solid (density $\sim$3 g cm^{-3}) matter of the GCR and SCR particles is given in Table I.

GCR fluxes are fairly constant, with solar activity being the dominant source of variation. The lowest and highest GCR fluxes are during periods of the 11-year solar cycle with the maximum and minimum solar activity, respectively.[4] Higher fluxes of GCR (by factors of a few times) are present in the local interstellar space beyond the heliosphere and could be present in the inner solar system during prolonged periods of unusually low solar activity, such as occurred during 1645–1715 (the Maunder minimum).[1,4] While heavy nuclei in the GCR are mainly stop by ionization energy losses in the outer few centimeters before they can react, most GCR protons and α particles react and produce a cascade of secondary particles, including many pions and neutrons. These secondary particles, especially the penetrating neutrons, induced all types of nuclear reactions down to depths of meters in large objects exposed to GCR particles.[5]

SCR fluxes vary from essentially nothing for most of the time to $\sim 10^6$ cm^{-2} s^{-1} at the peak of the 4 August 1972 flare. Observations of event-integrated solar particle fluxes over the last three solar cycles (1954–1986) have been summarized.[9,10] From 1956 to 1986, there have been $\approx$116 events with total event-averaged omnidirectional fluences above 10 MeV of $> 10^7$ protons cm^{-2} s^{-1}.[10] Average fluxes of solar protons over periods of $\sim 10^4$ to 5×10^6 years have been determined from measurements of radionuclides in lunar samples[1] and are $\sim$100 protons cm^{-2} s^{-1}. Almost all SCR nuclei heavier than protons and most solar protons are stopped by ionization energy losses in the outer $\sim$0.1–1 cm of matter in space.[1,5] The few reactions induced by SCR particles are low-energy ones that emitted few secondaries and produce residual nuclei close in mass to that of the target nucleus.

Table I. Energies, mean fluxes, and interaction depths of galactic and solar cosmic-ray particles.

Radiation	Energy[a] (MeV nucleon^{-1})	Mean flux (cm^{-2} s^{-1})	Effective depth[b] (cm)
Galactic cosmic rays			
Protons & α particles	$\sim$100–3000	$\approx$3	$\approx$0–100
VH, VVH nuclei ($Z>20$)	$\sim$100–3000	$\approx$0.03	$\approx$0–10
Solar cosmic rays			
Protons & α particles	$\sim$5–100	$\sim$100[c]	$\approx$0–2
VH, VVH nuclei ($Z>20$)	$\sim$1–50	$\sim$0.03[c]	$\approx$0–0.1

[a] Typical energies, actual energies range to lower and much higher values.
[b] Assuming typical lunar rock or meteorite densities ($\sim$3 g cm^{-3}).
[c] Long-term averages, actual fluxes vary from zero to much high values.

PRODUCTS FROM COSMIC-RAY INTERACTIONS

There are two major types of cosmic-ray products that can be detected in extraterrestrial matter as having resulted from cosmic-ray interactions: rare nuclei and "tracks." The cosmogenic nuclei that can readily be identified as having been produced by cosmic-ray-induced reactions are radionuclides (like ^{10}Be) and the minor isotopes of the noble gas (like ^{21}Ne) that are normally not present in matter.[1,2] GCR particles can produce almost any nucleus lighter in mass than the target,[5] and the types of reactions vary from high-energy spallation reactions, such as ^{56}Fe(p,X)^{10}Be (where X can be any of a great variety of nucleon and particle combinations) to low-energy reactions induced by low-energy secondary neutrons, such as ^{24}Mg(n,α)^{21}Ne. The low-energy protons and α particles in the SCR mainly induce reactions that produce residual nuclei close in mass to the target,[5,9] such as ^{28}Si(p,n2p)^{26}Al and ^{56}Fe(α,n)^{59}Ni.

The paths traveled in certain crystalline dielectric phases (e.g., certain minerals like olivine and pyroxene) by individual cosmic-ray nuclei with $Z \geq 20$ near the end of their ranges contain enough radiation damage that they can be etched by chemicals and made visible as tracks.[1,2,11] The heavy cosmic-ray nuclei that produce tracks are usually classified as the VH (very heavy) group ($20 \leq Z \leq 28$, although mainly iron nuclei) and the VVH group ($Z \geq 30$), with the ratio of VH to VVH nuclei being $\approx$500-700.

The products from the interactions of cosmic-ray particles and their secondary particle have been measured in extraterrestrial matter with a wide distribution of sizes, ranging from small pieces of cosmic dust to meteorites (which typically have preatmospheric radii of ~5-50 cm) to lunar samples. Secondary particles made by the interaction of the primary GCR particles are usually important in producing cosmogenic nuclides: in the Moon there are about 7 neutrons produced per primary GCR particle.[5] In the Moon and most meteorites, nuclear reactions induced by secondary particles are more probable than those from the primary GCR particles.

FLUX VERSUS DEPTH PROFILES

The distributions of cosmogenic products in meteorites and lunar samples often have been studied. These measurements imply a build up of the fluxes of secondary particles from GCR interactions for some distance inside these objects, the amount of build up being dependent on the energies necessary to induce nuclear reactions.[5,6] Only for high-energy ($E \gtrsim 1$ GeV) particles or for large (radii greater than ~300 g cm^{-2}) bodies are there decreases in flux near the center of a meteorite.[6] The largest increases in the fluxes of cosmic-ray particles are for neutrons, with the amount of the increase tending to be inversely proportional to the neutron's energy. High-energy ($E_n \gtrsim 100$ MeV) neutrons have very little increase with depth near the surface of an extraterrestrial object while thermal ($E_n \lesssim 1$ eV) neutrons tend to increase by large factors away from the surfaces of large (radii $\gtrsim 100$ g cm^{-2}) objects.[7,8] Most cosmogenic neutrons are made with energies of ~MeV, and it is difficult to slow them to thermal energies by scattering unless the object is big (radii greater than ~75 g cm^{-2}) and/or the hydrogen content of the object is high.[7,8] In such objects the flux of low-energy neutrons is very low near the surface because of neutron leakage into space.[7,8] Similar distributions of thermal neutrons will occur in large spacecraft, especially those with much hydrogen-containing material.

While the energetic GCR primary protons and α particles and their secondary particles are very penetrating in matter and have fluxes that vary slowly with the object's size or a sample's location, heavy nuclei ($Z \geq 20$) and solar energetic particles have flux-versus-depth profiles that vary considerably with depth. The heavy nuclei are rapidly stopped by ionization energy losses within $\sim$ 10 cm for GCR energies and $\sim$ 1 mm for the heavy nuclei from the Sun.[1,11] The relatively low-energy protons from solar-flare events also are also rapidly stopped in extraterrestrial matter, usually within less than 1 cm.[5,9]

The production rates of tracks and of several radionuclides made by a variety of nuclear reactions are shown as a function of depth in the Moon in Fig. 1. This figure illustrates the great spread in production profiles that exists for various cosmogenic products in matter exposed to cosmic-ray particles in space. VH nuclei in the cosmic rays only penetrate millimeters (for SCR) to centimeters (for GCR) in solid matter exposed in space before they are stopped. Similarly, protons and α particles emitted by solar flares are mainly stopped within a centimeter or so, although the fluxes of SCR particles vary considerably with time. The profile for ^{56}Co and for the top $\sim$1 cm of ^{26}Al in Fig. 1 result from solar-proton reactions in the Moon. High-energy primary and secondary GCR particles, such as those that make ^{10}Be, show mainly a decrease with depth. The secondary particles, especially neutrons, made by the cascade induced in matter by the high-energy protons and α particles in the GCR can be important meters deep in solid bodies in space. Medium-energy (E_n $\sim$ 10–50 MeV) neutrons contribute significantly to the production of ^{39}Ar and ^{26}Al, and their production profiles show increases to depths of $\sim$5–50 cm in the Moon. Neutron-capture-produced ^{60}Co has the greatest increase in a large object and has the deepest peak rate,[7,8] usually at depths of $\sim$50-100 cm.

TEMPORAL VARIATIONS IN COSMIC RAY FLUXES

Cosmogenic products have allowed us to determine the nature of the cosmic rays in the past. Several radionuclides with half-lives of the order of a million years have shown that the average fluxes of cosmic rays over the last 10^6 years are not very different than the contemporary fluxes. The main variations seen for GCR-produced nuclides, production rate changes of a factor of $\approx$2, have been due to the modulation of GCR particles by solar activity, mainly the 11-year solar cycle.[4] During the Maunder minimum, GCR production rates increased relative to those during a typical solar minimum.

Much larger fluctuations have been seen in the fluxes of energetic protons from the Sun over time periods up to a few million years.[1] The intensities of solar particles in individual solar flare events has only been studied for $\approx$30 years.[9,10] The similarity of long-term-averaged solar-proton fluxes with those observed now implies that huge solar-energetic-particle events, larger than those of 23 February 1956 and 4 August 1972, are rare.[1,10] These and several other large solar-particle events since 1956 had, for energies above 10 MeV, omnidirectional fluxes at their peaks of $\sim 10^6$ protons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and fluences integrated over the few days of the event of $\sim 10^{10}$ protons cm^{-2}.[9,10] The probabilities of events with integrated fluences much above $\sim 10^{10}$ protons cm^{-2} can not be predicted but appear to be fairly low.[10] As even events with peak fluxes of $\sim 10^6$ protons cm^{-2} s^{-1} (which usually occur a few times per 11-year solar cycle) can cause significant radiation damage, spacecraft that will be in space away from the shelter of the Earth's magnetic fields for long periods of time will probably have a good chance of encountering such high particle fluxes.

SUMMARY

The concentration-versus-depth profiles of cosmogenic products measured in lunar samples and meteorites can be used to help to estimate the fluxes of heavy cosmic-ray nuclei, energetic primary and secondary GCR particles, thermal neutrons, and solar energetic particles in any matter in space as a function of location and the object's size. These measured concentrations of cosmogenic products and their distributions also can be used to test computer codes that model the interactions of cosmic-ray particles with spacecraft and instruments in space. The Sun controls the variations in the intensities of GCR particles, with the major fluctuation (by a factor of ≈ 2) being over the 11-year solar cycle. Energetic solar particles are very episodic, although they seldom occur during the few years around solar minimum. The probabilities for the occurrence of very large fluxes of solar particles (peak fluxes above 10 MeV of $>10^6$ protons cm^{-2} s^{-1} or event-integrated fluences $>10^{10}$ protons cm^{-2}) can not be well predicted, although the long-term record in lunar samples suggests that such huge flare-particle events are very rare.

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REFERENCES

1. R. C. Reedy, J. R. Arnold, and D. Lal, Annu. Rev. Nucl. Part. Sci. 33, 505 (1983); and Science 219, 127 (1983).
2. D. Lal, Space Sci. Rev. 14, 3 (1972).
3. P. Englert, R. C. Reedy, and J. R. Arnold, Nucl. Instrum. & Methods A262, 496 (1987).
4. R. C. Reedy, J. Geophys. Res. 92, E697 (1987).
5. R. C. Reedy and J. R. Arnold, J. Geophys. Res. 77, 537 (1972).
6. R. C. Reedy, J. Geophys. Res. 90, C722 (1985).
7. M. S. Spergel, R. C. Reedy, O. W. Lazareth, P. W. Levy, and L. A. Slatest, J. Geophys. Res. 91, D483 (1986).
8. R. E. Lingenfelter, E. H. Canfield, and W. N Hess, J. Geophys. Res. 66, 2665 (1961).
9. R. C. Reedy, Proceedings of the 8th Lunar Science Conference (Pergamon Press, New York, 1977), p. 825.
10. J. N. Goswami, R. E. McGuire, R. C. Reedy, D. Lal, and R. Jha, J. Geophys. Res., in press.
11. R. L. Fleischer, P. B. Price, and R. M. Walker, Nuclear Tracks in Solids (University California Press, Berkeley, 1975).

Fig. 1. Production rates for heavy (VH) nuclei tracks and various radionuclides as a function of depth in the Moon (density = 3.4 g cm^{-3}). The shaded region for tracks of VH nuclei reflects the uncertainties in the average fluxes of the low-energy VH nuclei in the SCR.[1] Deeper than ~0.1 cm, VH nuclei in the GCR dominate. The units for the production of ^{60}Co are atoms per minute per gram of cobalt;[7,8] the other radioactivities are in units of atoms per minute per kilogram of sample.[5] (The decay rates assume that the radionuclide's activity is in equilibrium with its production rate.) At depths of $\lesssim$1 cm, SCR production of nuclides usually dominates and appears as a steeply dropping curve (^{56}Co and ^{26}Al). Production of ^{10}Be mainly by high-energy GCR particles results in a profile with very little increase with depth, whereas production by low-energy secondary GCR neutrons results in big increases (^{39}Ar and ^{60}Co).