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# Fluence Rates, Delta Rays and Cell Nucleus Hit Rates from Galactic Cosmic Rays

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The dose deposited by galactic cosmic rays (GCR) in the bodies of space travelers outside the magnetosphere is delivered in a much different way from the dose deposited in situations of radiation exposure of concern on Earth. Galactic (and solar) particles consist of high-energy charged protons, helium and heavier ions that readily penetrate the spacecraft and the travelers' bodies, either undergoing the occasional *nuclear* interaction, breaking up into secondary high energy particles (mainly in the forward direction) or just continuing through the spacecraft and the bodies of the travelers, all the time losing energy through *electromagnetic* interactions. In both cases, the energy of the particles is being absorbed by the body from the high energy charged particles having *very long* tracks (usually many centimeters in length) as the particles slow down, with delta rays (electrons) emanating radially at various angles on all sides. A comprehensive treatment of charged particle tracks and the biological importance of their resultant *track structure* (i.e., patterns of energy deposition) can be found in this section on Track Structure. This paper will first discuss fluence rates and hit frequencies of GCR primary and secondary particles through a typical cell nucleus within the human body and then consider effects of the "spread-out" nature of the tracks due to the cloud of emitted electrons known as *delta rays* that emanate from the tracks as they lose energy.

Annual total *dose* rates and *dose equivalent* rates from the galactic cosmic rays on trips outside the magnetosphere are on the order of 20 cGy/y and 60-70 cSv/y, respectively, at solar minimum (the time in the solar cycle of maximum GCR dose rates) (Cucinotta et al., 2011). Here we discuss this dose rate in terms of *fluence rates* of particle tracks through typical biological targets.

In the *continuously slowing down approximation* (csda), the well-known equation:

$$\phi = D\rho/L \qquad (1)$$

yields $\phi$, the fluence of heavy particle tracks in number per unit area, if we know the absorbed dose, $D$ (energy absorbed per unit mass), $\rho$, density of absorbing material (mass per unit volume) and the $LET_\infty$, $L$ (energy loss per unit length). When the radiation includes particles of different LET's, the *track-averaged* LET is used. To calculate a fluence rate through a target, i.e., a target hit rate, the fluence rate, $\phi_r$, is multiplied by the cross-sectional area of the subtended target. For a spherical target of area 100 μm$^2$, a typical size of a cell nucleus, the hit rate $\phi_{r,100}$ (in hits/unit time) is written (with $\rho$ = 1 g/cm$^3$ for water) and dose rate $\dot{D}$ in (Gy/unit time) and L (in keV/μm):

$$\phi_{r,100} = 624\ \dot{D}/L \qquad (2)$$

It is important to keep in mind that in space, tracks traverse small targets randomly and *not very often*. The GCR are known to be isotropically and uniformly distributed in space outside the Earth's magnetosphere. This means we can consider them as being Poissonly distributed in space and time with mean values of their energy distributions (spectra) that have been measured for many years now in various spacecraft carrying charged particle spectrometers. In addition, the processes by which the particles change their identity (via nuclear interactions) and energy (via both nuclear and electromagnetic interactions) as they pass through matter are well-known, so reliable calculations can be made to obtain fluence energy spectra of the various particles at any depth within a spacecraft and body of a space traveler given incident energy spectra of all the GCR for a specified time period if sufficient details of their shielding composition and geometry are available. NASA has developed a computer tool, *Oltaris*, to make such calculations. Information about this tool is available at *Oltaris.larc.nasa.gov*.

As an example of a calculation of cell-hit numbers behind typical shielding in space, a spherical cell nucleus with cross-sectional area 100 $\mu m^2$ as the target would receive at Solar Minimum a proton hit about once every 3 days, a helium ion hit about once a month and an iron ion hit about once every 100 years (Curtis and Letaw, 1989). For the high Z components, calculations were made for the probability of two or more hits in a year in the same target nucleus. Here the radiation was split into several charge groups for convenience. The results are shown in Table I. We see that the probability of a cell nucleus in one year being hit once or more by particles with Z=10-28 is 12% and being hit *more than once* by any two particles in this charge group is less than 1%. For the Z=3-9 group which consists mainly of carbon, nitrogen and oxygen ions, the annual hit probabilities are 49% and 14%, respectively. From this we can conclude that over 90% of the cell nuclei hit in one year would be hit by only one heavy ion track in the 10-28 charge range as would 70% of the cells hit by at least one ion in the carbon-nitrogen-oxygen group.

**Table I.**
**Probability of cell nucleus hits annually by GCR and secondaries in a shielded* spacecraft at Solar Minimum**

| Charge Group | ≥ 1 hit | ≥ 2 hits |
|---|---|---|
| 3 - 9 | 0.49 | 0.14 |
| 10 - 16 | 0.1 | $5.1 \times 10^{-2}$ |
| 17 - 25 | $1.6 \times 10^{-2}$ | $2.6 \times 10^{-4}$ |
| 26 - 28 | $9.9 \times 10^{-3}$ | $5 \times 10^{-5}$ |
| 10 - 28 | 0.12 | $8 \times 10^{-3}$ |

*The center of a 4 g/cm$^2$ spherical Al shell plus 5 g/cm$^2$ from the surface of a 30-g/cm$^2$ diameter water phantom

A calculation made with the *Oltaris* tool mentioned above using a GCR spectrum assuming a Solar Modulation Parameter of 410 to simulate solar minimum conditions in 2009, which resulted in an increase in GCR intensities, produced similar numbers for hit probabilities, this time for a shielding configuration of concentric spheres of thickness 2 g/cm$^2$ aluminum, 1 g/cm$^2$ polyethylene and 3 g/cm$^2$ tissue. The results were obtained in terms of the number of hits in a year from tracks with LET's greater than 0.22 keV/μm (this includes all particles), 10 keV/μm, 100 keV/μm and 1000 keV/μm. The numbers were 256, 1.22, $5.84 \times 10^{-2}$ and $2.36 \times 10^{-4}$, respectively. Here we see that there was only, on average, one track per year traversing a 100 $\mu m^2$ sphere with LET greater than 10 keV/μm and less than one hit per day of any particle, including protons.

An overall conclusion here is that, on average, all tracks from GCR will enter the body of a space traveler as single particle tracks, with on the average considerably more than a day between hits of cell nuclei even for protons.

There are two other characteristics of these tracks that are important. First, they have high energies so that a track that hits one cell nucleus will hit more than one, probably hundreds or even thousands depending on its range before it comes to rest. This creates a long linear array of affected cells within a tissue. This has been denoted a microlesion (Todd and Walker, 1984, see also Cucinotta et al., 1999). The cells hit will absorb significant energy as the track traverses them. Whether the cell survives or is inactivated will depend, of course, on how the energy is absorbed by the cell and how the cell deals with the subsequent damage. So one track does not cause just one cell hit but many within an organ. This microlesion of affected cells may be important in causing certain effects that do not occur for low LET radiation, where the tracks are electron tracks and are very short and more homogeneously distributed due to multiple scattering (Grahn, 1971, Cucinotta et al., 1999, Brooks et al., 2001).

The other important characteristic of a high energy GCR particle track is the cloud of electrons or “delta rays” that is produced as it ionizes the nearby atoms it traverses as it slows down. This cloud has been called the “penumbra”, with the “core” denoting the very central region with the highest energy density (only reaching to ~10 nanometers or less from the trajectory). The electrons are emitted at angles to the track trajectory that depend on their initial energy. Maximum energy electrons will be ejected in the forward direction. Because of their charge and small mass, the delta rays (i.e., electrons) scatter in various directions as they slow down and those with the highest energies can reach many cells.

A few calculations have been made of how many additional cells are hit by these delta rays for every cell hit by a core. Assuming the Katz track model (Katz and Butz, 1969, Kobetich and Katz, 1969) for high energy charged particles, it can be estimated that roughly 10 cell nuclei (of 100 $\mu m^2$ area) will be hit by deltas for every one hit by an iron particle penetrating 10 $g/cm^2$ water at 1977 Solar Minimum as shown in Fig.1 (from Cucinotta et al., 1998). Here the circles which denote a 1 mGy cutoff in the track width is assumed to be a reasonable assumption for the average single hit electron event size and can be taken as an approximation of the average distance of single delta ray penetration lateral to the track. We see from the figure that for iron ions (z=26), the ratio of the curve labeled “circles” (1 mGy cutoff) to that labeled “diamonds” (the core only) is 10.

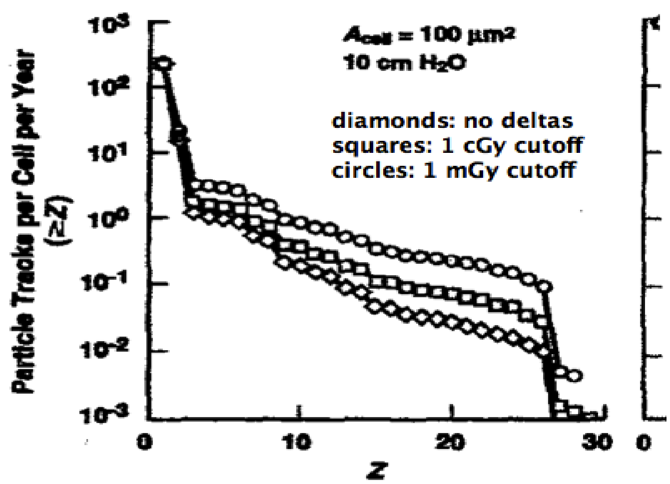


Figure 1. Integral number of particle tracks per cell per year from GCR exposures at solar minimum as a function of ion charge behind 10 $g/cm^2$ of water for cell area of 100 $\mu m^2$. Diamonds are neglecting the deltas, squares and circles are assuming 1 cGy and 1 mGy track-width cutoffs, respectively.

Another calculation for the number of cell nuclei hit by delta rays per track core of 1000 MeV/amu iron ions was made by Brooks et al., 2001. Here rat lung stem cells were assumed with spherical volumes 268 $\mu m^3$ to be closely packed and having cross sectional areas about 50 $\mu m^2$. The calculation yielded 32 cell nuclei hit by deltas to every one hit by the core of a high energy iron ion.

Because at a given velocity the number of deltas emitted is proportional to $z^{*2}$, there are more deltas being emitted by high energy iron ions per unit length than any other component of the GCR. Therefore, these numbers are maximum numbers of cell nucleus hits by deltas for any cosmic ray ion.

We conclude from the above considerations that no more than 10-30 nearby cell nuclei will be hit by a delta ray for each cell nucleus hit by a core of a high energy heavy ion.

We now turn to microdosimetric considerations to consider whether neighboring cell nuclei are hit by more than one delta. Delta rays are emitted stochastically along the track and because of their small mass undergo many multiple scatterings before coming to rest. Such processes are conveniently treated by Monte Carlo techniques (Plante and Cucinotta, 2009, see also articles in the Radiation Chemistry section). One calculation of the frequency-averaged specific energy[1] for nanometer-sized targets as a function of distance from the track core for 1000 Mev/amu iron ions was made by Cucinotta et al., 2000. The results are shown in Fig. 2, for three small targets: cylinders with diameters and lengths 2 by 2, 10 by 5 and 25 by 25 nanometers, respectively. These volumes are representative of an element of DNA, a nucleosome and an element of chromatin fiber, respectively.

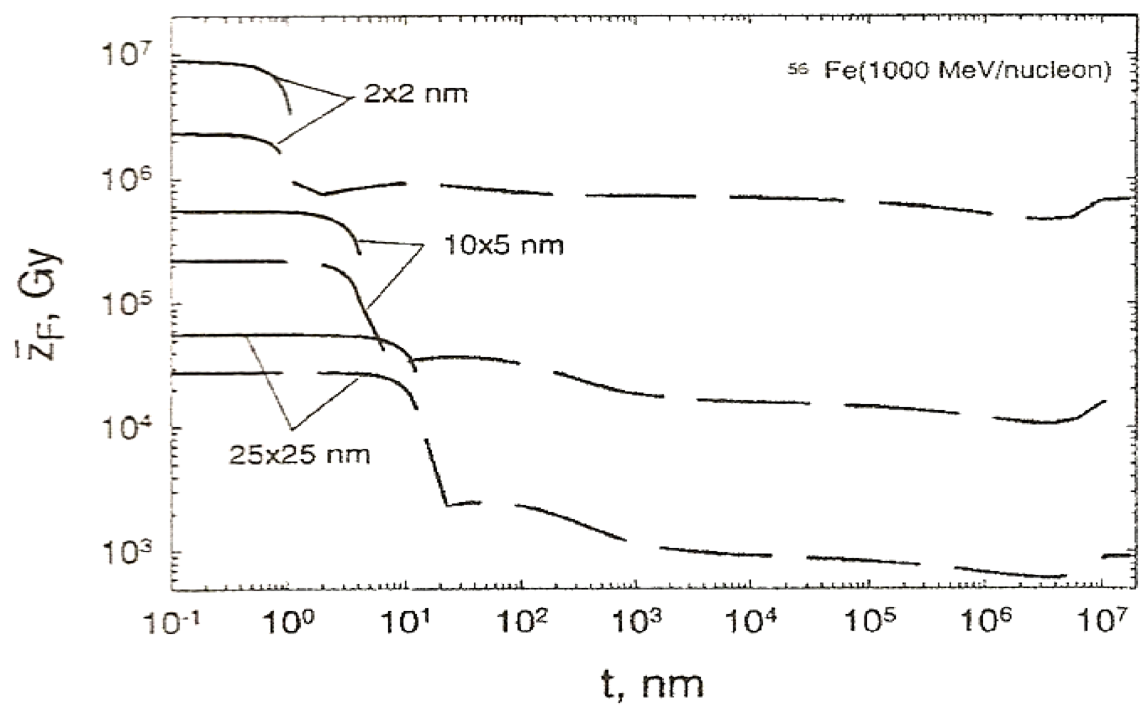


Figure 2. Frequency-averaged specific energy for three cylindrical target volumes: a DNA element (2x2 nm), a nucleosome (10x5 nm), and a chromatin fiber element (25x25 nm) as a function of distance from the track core of a 1000 MeV/amu iron ion. The dashed lines show the results of the model calculation. (Cucinotta et al., 2000).

[1] Frequency-averaged specific energy is the total energy deposited in a specified volume divided by the number of energy depositions in the volume and its mass.

Targets in neighboring cell nuclei are separated from each other by the surrounding cytoplasm of each cell and for most cells are on the average at least 4 µm apart. The flatness of the curves in Fig. 2 above $4 \times 10^3$ nm (4 µm) indicate that at least for targets of this size, only one electron is hitting the target.

It is not known whether these single delta electrons add significantly to the biological damage the tissue must handle. It has been conjectured, however, that single delta rays (ranges ≥~4 µm) will not add significantly to the risk of any effects at low fluences from the GCR (Curtis, 2012). If true, the main effects of concern will be a function of the number of delta electrons from the track per unit length (i.e., $z^{*2}/\beta^2$) and not their energies. One way to check this is to perform appropriate low fluence experiments with ion beams of the *same* $z^{*2}/\beta^2$ to compare the results at the same fluences (or measure the action cross section for the effect for each ion, which is the slope of the effect vs. fluence curve at low fluences). In Table II various ion beams are given with $z^{*2}/\beta^2 = 1000$ along with their LET's.

**Table II.**

**Ions with the same $z^{*2}/\beta^2$**

| **Ion** | $z^{*2}/\beta^2$ | **LET keV/µm** | **Energy MeV/amu** | **Residual Range g/cm²** |
|---|---|---|---|---|
| $^{56}Fe$ | 1000 | 164.5 | 707 | 16.33 |
| $^{40}Ca$ | 1000 | 150 | 272 | 4.36 |
| $^{28}Si$ | 1000 | 136 | 108 | 1.26 |
| $^{20}Ne$ | 1000 | 124.5 | 50.5 | 0.46 |

Here the lighter ions have such short residual ranges that only a few layers of cells should be irradiated because for samples many layers thick, the lighter ions are changing their velocities appreciably as they slow down and the values of $z^{*2}/\beta^2$ will not stay constant throughout the sample. Experiments must be done to approximate the very low fluence rates in space. Although these fluence rates are not feasible in an accelerator setting, many small daily fractions would simulate to some degree these very low fluence rates. In particular, a fluence hit rate of 0.1 nuclear cell hit per fraction per cell layer would keep the probability of two or more nuclear cell hits per fraction per cell layer to 0.0047. For iron ions at 1000 MeV/amu and a cell nuclear cross section 100 µm$^2$, that would be a dose per fraction of 24 mGy.

In conclusion, we have seen that space travelers will be experiencing galactic cosmic ray tracks singly as long tracks usually centimeters or more in length hitting any typical cell nucleus very seldom, once every three days for protons and less seldom for the heavier components of the GCR and their nuclear secondaries. However, each track will hit many cells as it slows down through the body. Delta rays (electrons) are emitted as the track ionizes the atoms through which it passes. These deltas can travel through many cells laterally to the track but these cells will usually experience only one delta per heavy particle track and the damage (i.e., energy absorbed in the cell) from these single deltas is small compared to that from the rest of the track and, we suggest here, can be neglected. Thus, it is reasonable to think in terms of fluences and fluence rates of GCR and nuclear secondaries rather than dose and dose rates. It is also possible that a quantity that is a measure of the number of electrons emitted per unit track length (e.g., $z^{*2}/\beta^2$) might be a better quantity than LET to characterize the radiation risk from these cosmic ray particles. These suggestions have been discussed for some time in the literature (e.g., Curtis, 1970, Katz, 1970, Curtis et al., 1992, Curtis et al., 1995, NCRP, 2001). They have been accepted by NASA in developing the 2010 Cancer Risk Projection Model (Cucinotta et al., 2011).

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