

# THE HEAVY PARTICLE HAZARD - WHAT PHYSICAL DATA ARE NEEDED ?

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It is impossible at present to evaluate adequately the radiation hazard from heavy galactic cosmic rays to astronauts on extended missions. Both physical and biological data are sorely needed for the proper assessment of the risk on missions lasting a year or longer outside the earth's magnetosphere.

The physical data required fall into three main categories:

1. Spectral Characteristics. From the relative abundance of the high  $Z$  nuclides and the limited data already obtained at solar minimum in the low energy region, it is clear that the flux of very high LET particles (above  $2 \times 10^3$  MeV cm<sup>2</sup> / g) will be predominantly low energy ions ( $< 500$  MeV / nucleon) in the iron group ( $26 \leq Z \leq 28$ ). Thus, it is important to determine the shape of the low energy portion of the spectrum during the next solar minimum ( $\approx 1976$ ), when galactic fluxes reach their maximum values.

2. Nuclear Interaction Parameters. Although ionization will be the main energy loss process for the heavy ions, a considerable fraction will also undergo nuclear collisions, fragmenting into particles of lower charge but perhaps greater range than the primary particle. Because the mean free path for interaction ( $\approx 15$  g/cm<sup>2</sup>) is on the order of the probable shielding available for critical body organs (the eye, brain), it is necessary to know the secondary production characteristics in order to make a reasonable estimate of particle fluxes within the body organs in question. Results of a computer code are presented in which two different assumptions for the fragmentation parameters and their  $Z$  dependence (experimentally unknown at present) have been made.

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3. Track Structure. The spatial distribution of ionization surrounding a high energy, high  $Z$  ion plays an important role in determining the ultimate biological damage. Knowledge of track structure will help to predict biological effects and may be crucial in the all-important extrapolation from animals to man. A rough theory for calculating the dependence of the energy density in water as a function of distance from the track trajectory will be reviewed. Limited biological data at much lower energies suggest that the height of the shoulder of this curve (which is proportional to  $Z^2/\beta^2$ , not total LET) may be closely correlated to biological damage.

Data in the first category above must be obtained by spacecraft flying outside the magnetosphere during solar minimum and instrumented to measure the low energy portion of the high  $Z$  galactic component. The data in the second and third categories can be most reliably and readily obtained in earth-based laboratories (along with the necessary biological data). The requirement here is an accelerator of ions in the iron group up to the region of 300-500 MeV/ nucleon.

A convincing case has been made that on recent Apollo missions, astronauts have experienced within their eyes, and probably via direct retinal excitation, the effects of the passage of high energy heavy galactic cosmic rays (ref. 1). It remains to be determined the extent of any lasting, deleterious effects produced by such ions over a continuous extended exposure. At the present time, there are no data on the biological effects of such high LET penetrating radiation on man or animals. The reason for this, of course, is that no accelerator exists at present which can produce beams of heavy ions with sufficient penetration to attempt the type of biological experiments necessary for the proper evaluation of this hazard. There is

much to learn before we can be sure that astronauts on very long missions, that is, missions of a year or longer, will be safe from the continuous bombardment of these high LET particles.

In this paper we will not deal with the biological research that must be done to study the long term effects of such radiation, but instead will discuss the physical data necessary for an adequate evaluation of the problem.

The research falls into three main categories, each of which is interesting in its own right. These are presented in Table 1.

First, there is the radiation environment itself - what is the flux of these high energy, heavily ionizing ions; how many might be expected to hit

## PHYSICAL DATA REQUIRED

### RADIATION ENVIRONMENT OF HIGH ENERGY HEAVY IONS

#### Fluxes

Energy spectra (emphasis on energies  $< 500$  MeV/nucleon)

Solar modulation

### NUCLEAR INTERACTION PROPERTIES

Cross sections in aluminium and water (tissue)

Fragmentation parameters

### TRACK STRUCTURE

Radial energy density

Track core size

Correlation of structure to biological effects

a spacecraft on, say, a Mars mission? Of particular interest is the energy region just below 500 MeV/nucleon, where the penetration is still sufficient to be of concern and where the ionization (that is the LET) will also be high.\* Solar modulation is important since these lower energy particles are affected more than those of higher energy by the modulation mechanism. Long manned missions may be planned for solar inactive years to decrease the probability of encountering giant solar-particle events. If so, the galactic fluxes encountered will be near maximum.

Secondly, we must study the nuclear interaction properties of the particles involved in the materials of the spacecraft and the bodies of the astronauts themselves. No data are presently available on the cross sections of heavy ions in the 1 GeV/nucleon range in aluminum and water or tissue. The total non-elastic cross sections can be estimated with fair accuracy, but we must also know the fragmentation parameters associated with the various particle reactions. The fragmentation parameter for a given secondary particle type is either the probability of emission of the secondary, if less than unity, or the average number of secondaries per interaction, if greater than unity. Also, how is the energy shared as the two nuclei break up?

Does the resulting fragment continue with the same velocity, or is there significant change in the energy per nucleon of the emerging heavy particle?

These questions must be answered before a clear idea can emerge of the penetration characteristics of the heavy ions. Only then will it be possible to make accurate predictions of the fluxes of high  $Z$  ions at organs which may be critical in that they might accumulate enough damage to impair normal function.

Finally, there is the field of track structure. Here the interest is in the spatial distribution of energy deposition by the heavy ions as they slow down in tissue. What is the extent of the core of such an ion? What is its "radius of destruction"? Is the important physical parameter its LET or  $dE/dx$ , or does the diffusive character of the "electron penumbra" decrease its biological effectiveness to less than that of a lower energy ion at the same  $dE/dx$ ? These are all questions which bear directly on the biological effects of these ions. Since laboratory experiments may be performed with animals which have cells or cell nuclei with different sizes than the equivalent cells in man, it may be important to know as much as possible about the physical distribution of energy density around a heavy ion track in order to extrapolate results from animals to man.

We now review briefly some of the things we already know in these areas.

### Integral Number-LET Spectra

Considerable data have been obtained from satellites and balloons on the fluxes and energy spectra of heavy galactic particles during the last solar minimum period; that is, during the period of maximum galactic fluxes - 1964-66 (ref.2).

\* For orientation, a 500 MeV/nucleon iron nucleus has a residual range of  $10 \text{ g/cm}^2$  of water and an LET of  $2000 \text{ MeV cm}^2/\text{g}$  ( $200 \text{ keV}/\mu$ ).

In figure 1 we show the integral spectra not as a function of the energy or energy per nucleon as is usually presented, but as a function of the  $dE/dx$  or LET of the particles, which has more biological relevance. We note that the particles in the iron group ( $26 \leq Z \leq 28$ ) dominate the spectra at very high LET ( $> 1000 \text{ MeV cm}^2/\text{g}$ ) and also that the data is scanty - the solid curve stops at  $5000 \text{ MeV cm}^2/\text{g}$  corresponding to an energy of  $100 \text{ MeV/nucleon}$ . The dashed lines at high LET for each component are just guesses which are consistent with the low energy spectral behavior of the lighter components we know more about - protons and alpha particles. The dotted line at high LET was

calculated assuming a sharp low-energy cut off in the iron spectrum at  $100 \text{ MeV/nucleon}$ . We conclude that more data are needed on the spectra of the very heavy, i.e. iron group ions, in the energy region just below  $300 \text{ MeV/nucleon}$  (residual range in water:  $4\text{-}5 \text{ g/cm}^2$ ) during the next solar cycle minimum (1975-77). Since these particles are strongly affected by solar modulation mechanisms, it would also be of interest to determine when and to what extent the low energy fluxes of these heavy ions decrease during the cycle.

### Nuclear Fragmentation

For high energy heavy ion-nucleus interactions, we have only cosmic ray data to give us any feeling for the cross sections and types of secondaries involved. In figure 2 we show a compilation of

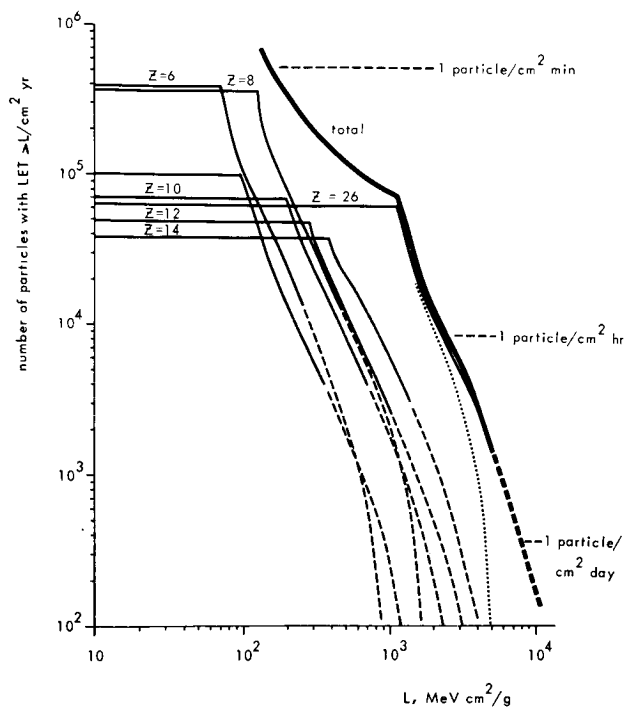


Figure 1. Integral number-LET spectrum for the galactic cosmic rays behind no shielding at solar minimum. The contribution of the various Z groups are also shown. The dotted line was obtained assuming a sharp low-energy cut off of  $100 \text{ MeV/nucleon}$  to the iron spectrum. The dashed lines represent regions where the data are lacking.

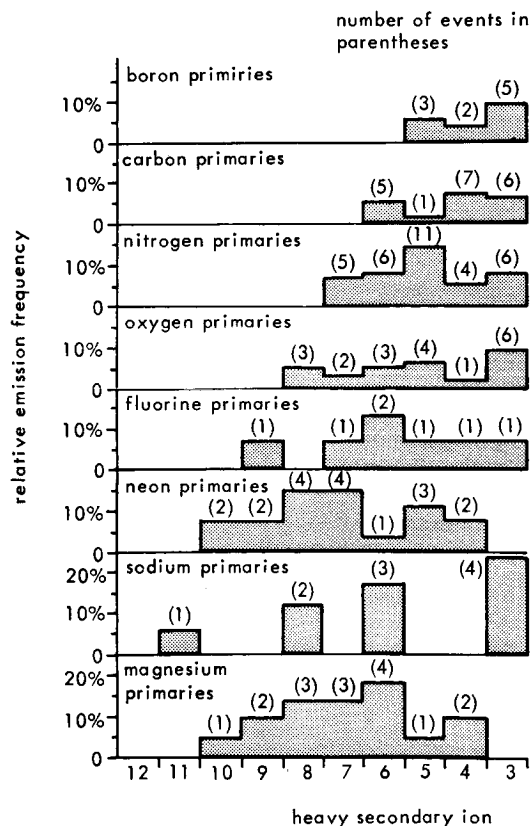


Figure 2. Compilation of experimental data for fragmentation parameters of heavy ions on the light elements (excluding hydrogen) in nuclear emulsions. The data come from rather old cosmic ray studies on balloons by the Bristol group (refs. 3 and 4).

data gathered from nuclear photographic emulsion on the fragmentation parameters in the light elements of the gelatine, i.e. carbon, nitrogen and oxygen. This was all the emulsion data in the literature a few years ago and was taken from the old compilations of the Bristol group (refs. 3 and 4). Now recent balloon flights could undoubtedly yield more data of relevance here, but the heavy elements in the emulsion (silver and bromine) will always give a certain amount of contamination trouble and considerable scanning would be required to get good statistics on each incident ion. Of lesser importance is the fragmentation in materials of which the spacecraft itself is made, for instance aluminum.

In the Space Physics Group at Boeing, a computer code has been developed to calculate the resultant fluxes and dose behind various shielding thicknesses for any incident galactic particle spectrum or combination of spectra. The results and details of the calculation have been presented earlier in this symposium (ref.5) and will not be repeated here, except to show the two sets of fragmentation parameters selected and the results of the dose rate calculations using the different sets. Figure 3 shows the two sets used. In set I, a constant probability for emission as a function of secondary  $Z$  is assumed, such that total charge is conserved. In set II, we try to reflect the possibility that fragments with  $Z$  close to two and close to the  $Z$  of the primary particle might be more probable than intermediate  $Z$  secondaries. In figure 4, the results of the dose rate as a function of depth for the iron group spectrum using the two sets are shown as the upper solid and dashed lines. There is a factor of two difference at  $60 \text{ g/cm}^2$  of water. Also shown are representative curves of the secondary dose rates from the product secondary fragments. These are just representative curves since there are actually twenty-five such secondary curves plus the uncollided iron curve contributing to the total.

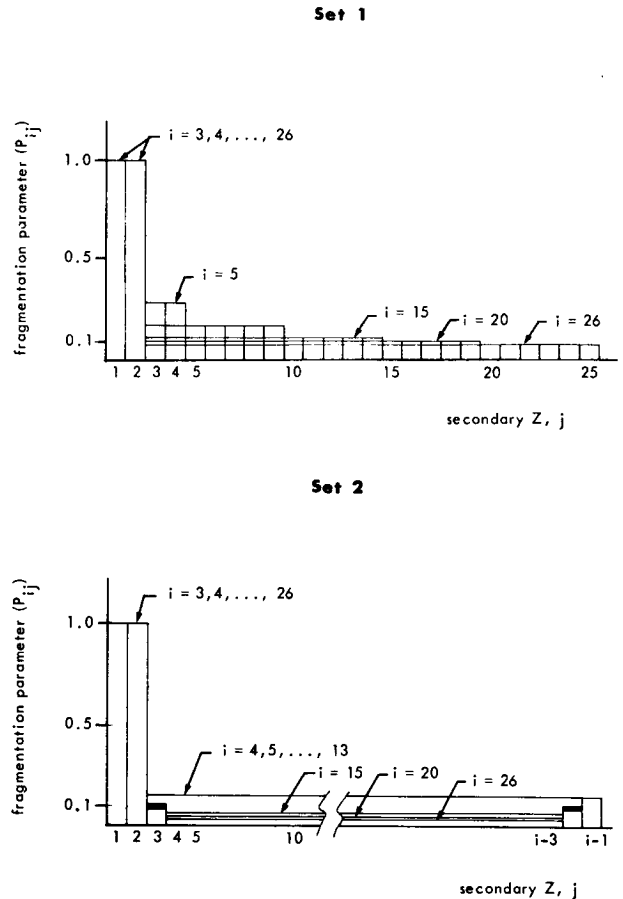


Figure 3. Two sets of fragmentation parameter secondary  $Z$  dependence assumed in the Boeing computer program mentioned in the text. Set I assumes a constant dependence on secondary  $Z$  plus charge conservation. Set II reflects the possibility that secondary ions with  $Z$  just less than the primary  $Z$  and secondary ions with  $Z$  close to that of  $\alpha$  particles might be more probable than intermediate  $Z$  secondaries.

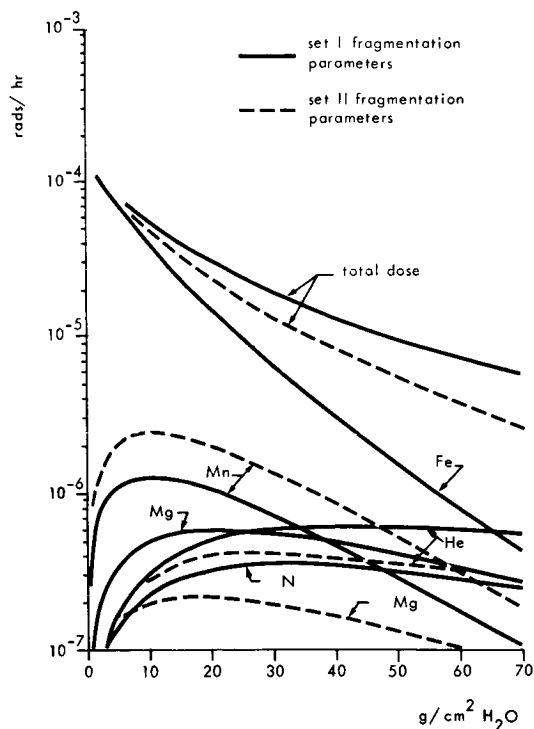


Figure 4. Dose rates as a function of depth from galactic cosmic rays of the iron group including secondary production as calculated by the Boeing code. Total dose rates as well as representative values from the secondary contributions are presented. The solid lines result from the Set I fragmentation parameters and the dashed result from the Set II fragmentation parameters presented in Figure 3. Note a difference of a factor of two in the total dose rates at 60 g/cm<sup>2</sup> of water.

We conclude that a better knowledge of the fragmentation parameters for such heavy ion break-ups is essential. At the same time, of course, this will provide us with more insight into nuclear structure and the way energy is shared in high energy nucleus-nucleus collisions, an area of interest to the nuclear physicist.

#### Track Structure

The physical distribution of energy deposition (ionization density) along the trajectory of a charged particle has been an area of increasing interest in recent years. One way of approaching this problem is by defining an average energy density

$\rho_T(r)$  as a function of distance from the track trajectory. The integral of  $2\pi r \rho_T(r)$  over distance from the trajectory yields the average  $dE/dx$  or  $LET_\infty$ :

$$LET_\infty = 2\pi \int_0^\infty \rho_T(r) r dr$$

The distance  $r$  is the perpendicular distance from the track trajectory. It is easier to study the quantity  $\rho_T(r)$  at large distances, say greater than 50-100 Å, than at small distances. At large distances, the only electrons present have come from the so-called "close collisions" and can be treated with the familiar Rutherford expression for free electrons. Two rather crude theories (refs. 6 and 7), which will not be discussed here, yield a dependence of  $\rho_T(r)$  going as  $Z^2/\beta^2$  of the particle in question and falling as a function of  $r$  as  $1/r^2$  up to distances which are still small compared with the range of electrons with maximum transferable energy. As we approach this range, of course, the function falls off much more rapidly. One estimation of the dependence of  $\rho_T$  on  $r$  for an iron nucleus of energy 500 MeV/nucleon is shown in figure 5. Here the ordinate is  $\rho_T$ , the "dose" in units of 100 ergs/g. Dose is in quotes here because it is not a dose in the strict sense of the word. It can be considered an average dose over distances along the track large enough so that  $dE/dx$  has meaning, that is, long compared to distances where the fluctuation of energy loss plays an important role. The dependence of this quantity at small distances is an open question at present. It is assumed to rise steeply because we know that the total integral must equal the total  $dE/dx$ , and subtraction of the tail contribution from the total leaves a large portion of the energy to be deposited in the core, at least one-half the energy. Hence the core is undoubtedly very important in producing biological effects. This nonuniformity of energy deposition implies that the average dose deposited by such particles or their total LET may

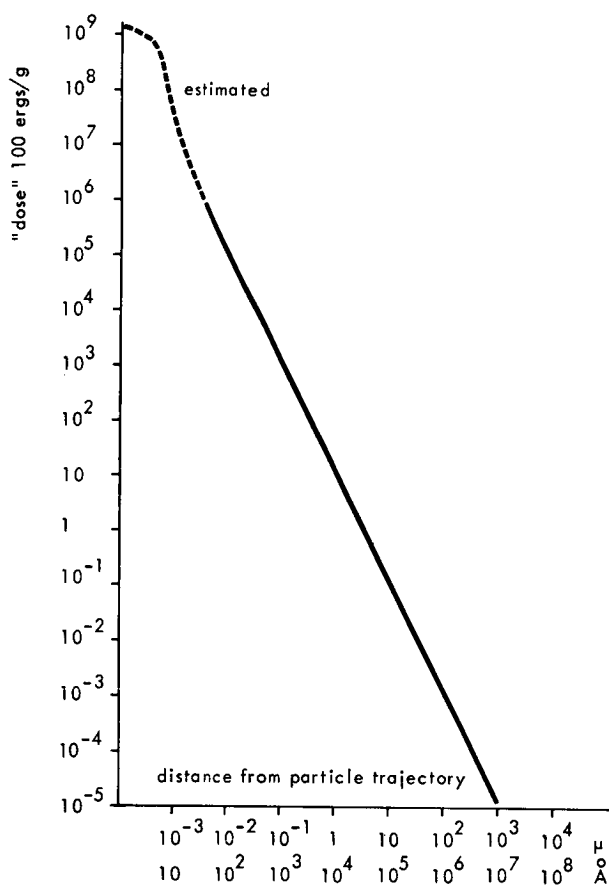


Figure 5. Estimation of the dependence of the energy density on distance from the particle trajectory of a 500 MeV/nucleon iron ion. The ordinate is not a true dose but can be considered an average dose over distances along the track long compared to distances where fluctuations of energy loss are important.

have little relevance to the evaluation of the hazard from these high-energy heavy ions.

There is evidence at much lower energy that the quantity  $Z^2/\beta^2$  is a more relevant quantity than  $LET_{\infty}$  to describe biological effects (ref. 8). It is well known that hypoxic cells are more radioresistant than oxygenated cells. The Oxygen Enhance-

ment Ratio (OER) is a measure of this difference in radiosensitivity for a particular type of radiation. An OER of 2.7 as measured in human kidney cells for X-ray irradiation, for instance, means that 2.7 times the dose is needed to produce the same effect on hypoxic cells as on well-oxygenated cells. If for a different type of radiation, the difference in radiosensitivity is less, the OER is lower. For an OER of unity, there is no difference in the radiosensitivity of oxygenated and hypoxic cells.

In general, the OER is closer to unity for radiations of high LET than for those of low LET. This is shown for two sets of experimental data in fig. 6a for the system of human kidney cells in tissue culture. The two sets of data differ in that the solid squares were obtained with high-energy heavy ions ( $\sim 7$  MeV/nucleon) all at the same velocity (ref. 9), and the open circles were obtained with alpha-particles at different velocities (ref. 10). We note that there is no overlap of the data. If, however, we plot the data against  $Z^{*2}/\beta^2$  instead of against  $LET_{\infty}$ , we obtain the results in figure 6b. Here  $Z^*$  is the charge of the particle, taking into account charge pick-up of the ion as it slows down. The data overlap to a much greater extent and are consistent with lying on the same curve. Thus we conclude that at least for this biological system and endpoint,  $Z^{*2}/\beta^2$  is a more relevant physical quantity to plot the biological results against. This correlation should be checked with other endpoints and, in particular, should be checked with high-energy heavy ions of importance in the galactic cosmic rays, where the "electron penumbra" is greater in extent, thus diffusing part of the energy deposited over a greater distance. The "close in" shoulder of the curve, as seen in fig. 5, rises as  $Z^2/\beta^2$ , so for high  $Z^2$  the shoulder will also be large. Core effects are extremely important because of the very high energy density in the core and it is even possible that new inactivation processes will come into play which are entirely absent at lower energy densities.

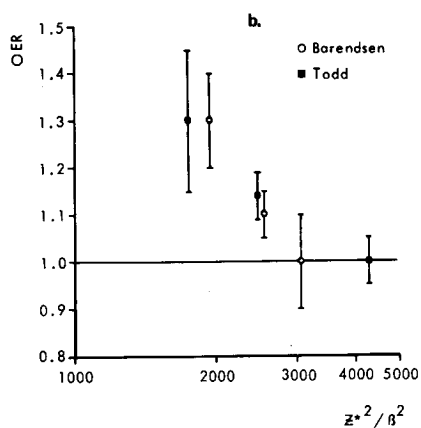
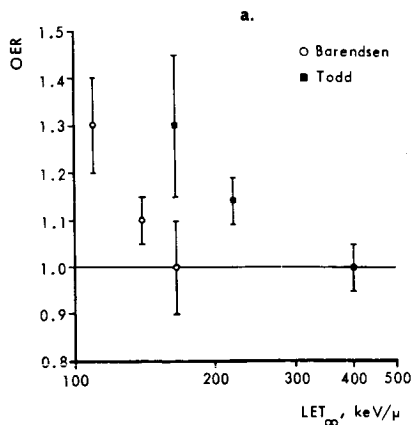


Figure 6. **a.** OER of human kidney cells (*in vitro*) from heavy ions at  $\sim 7$  MeV/nucleon (solid squares) and from low energy alpha particles (open circles) plotted against  $LET_{\infty}$ . **b.** Same data as in **a.** plotted instead against  $Z^*2/\beta^2$ , where  $Z^*$  is the effective charge of the ion (including charge pick-up) and  $\beta$  is the ratio of the velocity of the particle to that of light.

### Conclusion

We have mentioned several areas where physical data are needed in order to evaluate adequately the potential hazard of high-energy heavy ions in the galactic cosmic radiation to long manned missions outside our magnetosphere. The first, more data on the lower energy portion of the differential energy spectrum of the iron group, can be obtained in appropriately instrumented satellites during the next period of solar inactivity 1975-1977. The other two areas, nuclear interaction parameters in tissue and aluminum and the structure of the energy deposition along the trajectory of the tracks, appear to require an accelerator which accelerates ions of the iron group up to at least 300-500 MeV/nucleon. This information, along with the necessary biological information concerning the extent of damage and functional impairment to various critical organs, is necessary before we can confidently send manned expeditions to explore the near planets or establish bases for extended exploration of the moon.



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