# Current Problems in Astroradiobiology

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HUMAN FLIGHT in extra-atmospheric regions has created, for the radiobiologist, a number of new problems resulting from the fact that the radiation environment in space is peculiarly different from what natural and man-made terrestrial radiation sources can provide. Already before the advent of the satellite era, when the ceiling of manned aircraft progressed from the troposphere deeply into the stratosphere and finally all the way up to the top of the atmosphere, these new aspects were recognized. Especially one problem has found the early attention of those concerned with radiation hazards in high altitude flight. We mean the controversial issue of the heavy nuclei of the primary cosmic radiation. In 1948, soon after the discovery of the heavy nuclei, C. F. Gell[2] directed attention to the fact that components of the primary cosmic ray beam at extreme altitude and in free space would pose a special problem. Today, twelve years later, the question of the microbeam effectiveness of heavy nuclei is still unsolved. When radiation hazards in space flight are discussed nowadays, the newly discovered high intensity proton radiation fields of various origin are in the center of interest. In fact, attention seems so much concentrated on these new phenomena that the unsolved heavy nuclei problem is in a certain danger of no longer being seen in its true significance. This finds a certain justification in the circumstance that the exposure hazard in proton radiation fields is an acute one which might well reach or surpass the incapacitation threshold, whereas the heavy nuclei hazard is of the low-dosage long-term type in which the damage develops slowly and at first inconspicuously, yet ultimately might even be more serious in its irreparability.

The radiobiological problems concerning heavy nuclei irradiation have been discussed repeatedly and at length. The present debate, therefore, shall be limited to a few remarks on the methodics of future experimental work. Obviously, it makes a big difference in expenditure of time and money whether studies with biological specimens are carried out with balloons or space platforms in the region of the primary radiation or with simulated microbeams or artificially accelerated heavy ions in ground-based laboratories. It seems of interest, then, to review critically presently existing capabilities in latter respect. Artificially accelerated heavy nuclei have been successfully produced with the Heavy Ion Linear Accelerators (HILAC) of the radiation laboratories at Berkeley and Yale. The latest state of the art as reported by Heckman and colleagues[3] is that nuclei of carbon, nitrogen, oxygen, neon, and argon can be accelerated to a maximum kinetic energy of 10 Mev per nucleon. In terms of argon ions, this means a maximum kinetic energy of 400 Mev. While this is unquestionably a very impressive accomplishment opening new avenues for significant experimental work on the complex problem of the RBE (relative biological effectiveness) of densely ionizing radiations, it still is of interest in the present context to compare these artificial heavy nuclei to those of the primary cosmic radiation. Figure 1 shows a montage of micrographs of two heavy nuclei, one a calcium nucleus of the primary cosmic ray beam and the other an argon track from the HILAC as published by Heckman and his co-workers. Both tracks have been recorded

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From the U. S. Naval School of Aviation Medicine, Pensacola, Florida.

Presented at the Aerospace Medical Association in Miami, Florida, May 10, 1960.

with the same nuclear emulsion (Ilford G-5) and are shown at the same magnification. Since the atomic numbers (Ca:20, A:18) differ only slightly, the nuclei can be considered very similar.

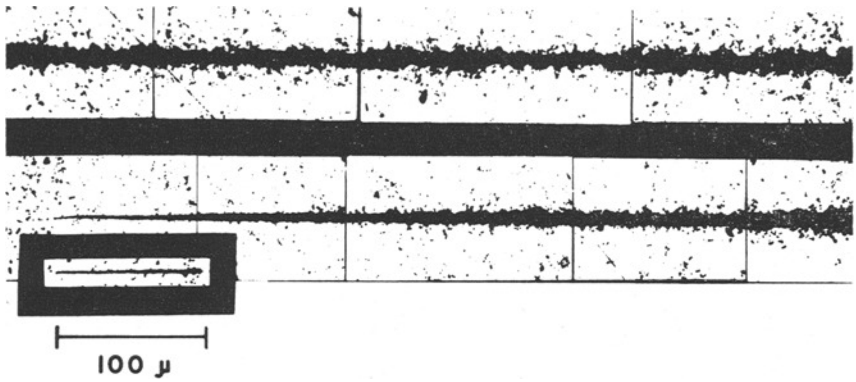


Fig. 1. Terminal Sections of Heavy Nuclei Tracks. Large track, broken in two sections, is Calcium (Z=20) track of primary cosmic radiation. Short track in inset at lower left is Argon (Z=18) track of HILAC. Both tracks are shown at same magnification. (Heckman et al,[3] Fig. 13, p. 555.)

In comparing the two tracks (Fig. 1) from a radiobiological viewpoint, two magnitudes have to be distinguished because they have a different meaning for the biological effects. These are the longitudinal and the radial extension of the two tracks. The former, the longitudinal extension, is strikingly greater for the cosmic ray nucleus indicating the much larger energy and range of the incident particle. Yet this circumstance seems only of secondary importance as far as the basic problem of the microbeam effectiveness of the nucleus on the structure of a single cell of living tissue is concerned. For this latter question, the radial spread of the ionization column is the decisive magnitude. For densely ionizing radiations from laboratory sources, such as protons, alpha rays, or fission recoil nuclei, the diameter of the ionization column is of the order of a few tenths of a micron. That means it is much smaller than the living cell. For the heavy nuclei of the primary cosmic ray beam, the diameter of the ionization column reaches the full size of a living cell due to the much higher speed of the nuclei, which in turn transmits to the secondary electrons a correspondingly higher speed, *i.e.*, range. This poses the question whether two different densely ionizing particles, which have the same LET (linear energy transfer, usually quoted in ion pairs per micron tissue), yet show a large difference in the radial spread of the ionization events about the center of the track, would produce the same damage in a living cell.

Unfortunately, present understanding of the primary biochemical changes released in the chromosomal material of a cell by ionization events is so poor that any specific inductive reasoning as to the possible significance of a different radial spread of these events seems out of reach. Merely a more general approach could be attempted with the following argument. Some lines of experimental evidence indicate that a large part of the radiation damage to cellular material originates from intermediate substances formed from water. These intermediate substances are radicals such as H, OH, $HO_2$, $H_2O_2$, and, if organic molecules are in close vicinity, also organic peroxides. If this is true, the zone of primary damage can be expected to be larger than the region to which the ionization events are limited because of the diffusion of the radicals in the cellular material. Since the lifetime of free radicals is extremely short, the diffusion length is also extremely small. Zirkle and Tobias[6] were the first ones to attempt a quantitative treatment of the kinetics involved. Others have resumed and further contributed to this discussion. A list of references is contained in Hutchinson's[4] study. In the present context, the estimates of the diffusion length are of special interest. They range (Hutchinson) from 30 to several hundred Angstrom Units (1 A$=10^{-7}$ millimeter$=10^{-4}$ micron). Figure 2 depicts in graphical form the dosage field of the terminal section for the Calcium nucleus of Figure 1. Superimposing upon this field the diffusion lengths for the radicals one sees that the tissue volume in which the primary processes occur is enlarged only very little. That means that the basic difference in the radial pattern of the ionization column between cosmic ray heavy nuclei and densely ionizing particle radiations from terrestrial sources should be fully reflected in the corresponding pattern for the primary chemical action. The conclusion, then, that two ionizing particles of the same LET, yet of different radial spread of the energy dissipation will produce the same damage in centrally traversed cells appears to stand on shaky grounds and in great need of experimental testing.

Though it seems questionable that a full solution of this problem could be accomplished in ground-based studies alone, an inspection of the dimensions of the HILAC track (Fig. 2) clearly indicates that it has the definite capability of contributing toward such a solution. It can be seen (Fig. 2) that the HILAC argon tracks enter the target with a radial spread of about 10 microns diameter for the 10 rep level. That is entirely the order of magnitude of cosmic ray heavy nuclei and distinguishes the HILAC quite basically from other laboratory sources of densely ionizing radiations. Of special interest in experimental studies with artificially accelerated heavy ions would be the range of low dosages down to the level of single traversals. This would directly bear on the cosmic ray heavy nuclei problem. To what extent the results of such experiments would be representative for the wide spectrum of heavy primaries, is of course, a complex question. Especially the so-called superheavy nuclei, *i.e.*, nuclei heavier than iron which have been recorded repeatedly with rockets in the primary beam entirely outside the atmosphere, should be considered in this respect. They are bound to gain importance for extended exposures of human beings at satellite altitudes and beyond.

As mentioned earlier, the discussion of radiation hazards in space flight centers at present very heavily on the newly discovered various

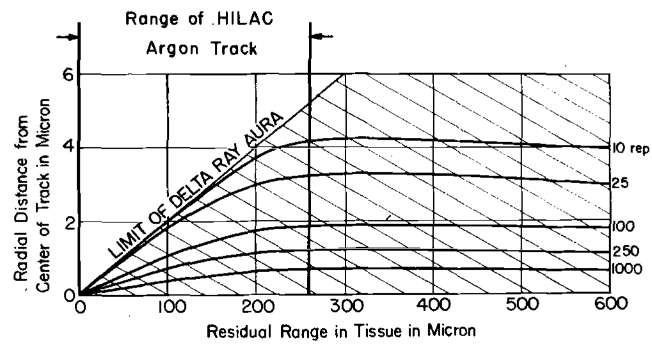


Fig. 2. Microstructure of Ionization Column in Tissue for Tracks Shown in Figure 1. Range of HILAC Argon track in tissue is 260 microns since stopping power of tissue is smaller than of nuclear emulsion. Note large radial spread in high energy section of HILAC track.

proton radiation fields in space. Among them, those produced by solar flares seem potentially the most dangerous. Disquieting is the fact that such events apparently are more frequent than has been assumed in the past, when only flare observations, but no cosmic ray recordings were available. Observations during 1959 in particular indicate that almost twice a month a greatly enhanced proton intensity prevails in interplanetary space as a direct consequence of flare activity on the sun.

In view of the assumption that in the near future, manned space flight will be limited to ballistic and orbital flights of shorter duration at satellite altitudes, it seems of interest to investigate what time reserve exists for starting re-entry procedures if a larger flare occurs while such a mission is in progress. The first clues of a flare in progress available on the earth are the visible observation of the flare and the increased noise level in long range radio communications. The latter is caused by ionization in the ionosphere produced by the enhanced ultraviolet intensity from the flare. This phenomenon is particularly disturbing for the commercial wireless service. These people, therefore, have been repeatedly the first ones to announce that a large flare was in progress. Both clues, visual observation and increased ultraviolet, arrive with the speed of light whereas the flare-produced protons travel at lower speeds depending on their energies. It seems of interest to evaluate this time lag for the various spectral regions of the flare-produced protons. Figure 3 shows the results of this evaluation. The abscissae of both graphs show kinetic energy in identical scales. The ordinate of the upper graph shows at the left proton speed in fractions of the speed of light c and at the right the corresponding delay in minutes with which protons would arrive at the earth behind a signal from the sun travelling at full c. The ordinate of the lower graph shows a typical integral energy spectrum of flare-produced protons compiled by Bailey[1] from data of various experimenters. It is seen that indeed a substantial time reserve exists for precisely that section of the energy spectrum which contributes the bulk of the additional intensity.

It should be emphasized that the assumption of a straight-line travel of solar protons from the sun to the earth holds only for a certain fraction of the flare-produced flux. The dynamics of interplanetary hydrogen plasma under the influence of solar activity is as yet incompletely understood since only the satellite era opened the way for direct measurements in deep space. According to present concepts, two acceleration mechanisms for solar protons have to be distinguished. One is acting in the flare itself. These protons, then, would travel the full distance from the sun to the earth essentially at the same high speed. The other mechanism is acting far away from the sun in the turbulent magnetic fields of the "solar wind." This very descriptive term has been suggested by Parker for the phenomenon of the coronal plasma expanding into interplanetary space. The plasma clouds move in a turbulent fashion at convective speeds of about 1000 km/sec. Due to the turbulence, plasma clouds create and carry their own magnetic fields which in turn exert accelerating influences on the hydrogen ions in the clouds. Obviously, the basic time-of-flight relationships underlying Figures 3 and 4 do not hold for protons accelerated by this mechanism. As these protons have travelled a shorter or longer fraction of the full distance from the sun at the low speed of the solar wind and have been accelerated gradually along tortuous trajectories in turbulent fields, they arrive at the earth with a delay of many hours or even of one or two days behind the visible light from the flare.

To be sure, magnetic deflection is acting also on the flare-accelerated protons. It was mentioned above that the concept of straight-line motion underlying the computations for Figures 3 and 4 holds only for a certain fraction of them, namely, those which make up the initial surge of the proton intensity during a flare. Other fractions seem to reach the earth in a more indirect way causing the proton intensity to remain elevated over a much longer period than the actual visible flare activity on the sun. Strong evidence for this proposition is offered by the fact that

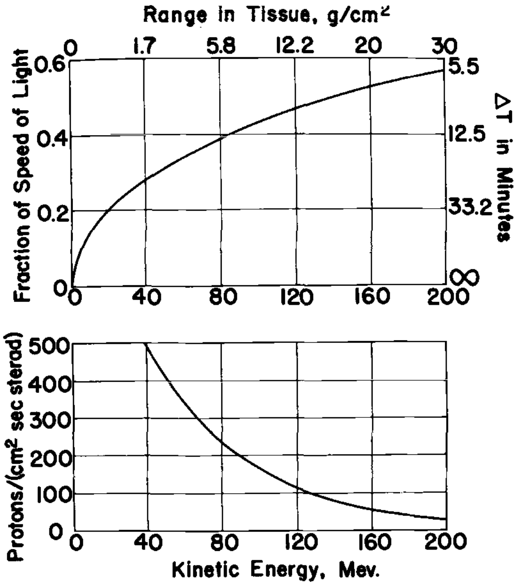


Fig. 3. Time of Flight of Solar Protons. Upper graph shows speed (left ordinate) and delay of arrival at earth behind light (right ordinate) as a function of kinetic energy. Lower graph shows integral energy spectrum of flare-produced protons. Note longer delays for larger particle intensities.

the instantaneous proton radiation during the large flare of February 1956 has reached the night side of the earth. During this flare, the sun was in the zenith over the northwestern edge of the Australian continent, yet all cosmic ray monitoring stations in the Western world, in Europe as well as in both Americas, experienced strong increases in "cosmic ray" intensity. Figure 6 shows an account of the sequence of events. The graph shows the cosmic ray surge at a station on the day side (Cape Schmidt) and on the far side (Ottawa) of the earth. It is interesting to notice that the steepness of onset as well as the peakedness and time of occurrence of the maximum differ considerably for the two locations.

The phenomenon that the total flare-produced proton flux at the earth is spread over a considerably larger time interval than the flare activity on the sun provides an additional time reserve for the re-entry of a space vehicle which wants to escape or minimize radiation exposure. Judged by the sea level neutron intensity, which can be shown to be a true measure of the extra-atmospheric intensity of

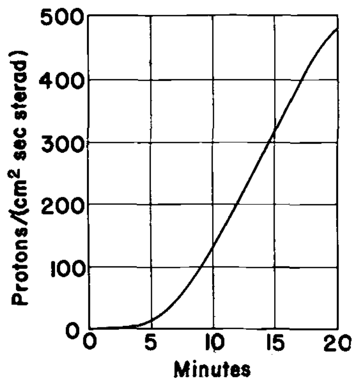


Fig. 4. Time of Flight of Solar Protons. Rise of Proton Intensity of Direct Beam of Spectral Type Shown in Figure 3: Assumed is essentially straight-line travel. Zero Time: Light from onset of flare arrives at earth.

ionizing particles, the integral exposure from the time of the beginning of the proton surge builds up as shown in Figure 5. The graph is based on observations of the sea level neutron intensity during and after the 1956 flare at Durham, New Hampshire. It is seen that even if a full hour has elapsed before a manned space vehicle has completed re-entry and is back behind the shield of the atmosphere, a substantial reduction of the integral dose would still be accomplished. Referring again to Figure 6, it can also be seen that this time reserve is markedly smaller at longitudes closer to the direct impact zone. In addition to that, a strong latitude effect also seems to exist for both the rise time and the integral dose. Yet a complete account of these relationships is beyond the scope of this treatise.

It is a very complex task to express all the new data on flare-produced proton beams in space in terms of tissue depth doses in an exposed human target. The old problem of medical dosimetry, a separate and accurate evaluation of "air" dose, tissue dose, and depth ton fluxes in space differs quite basically from that for terrestrial proton fields, such as resulting from reactor neutrons. For the details, the reader is referred to the earlier treatise.

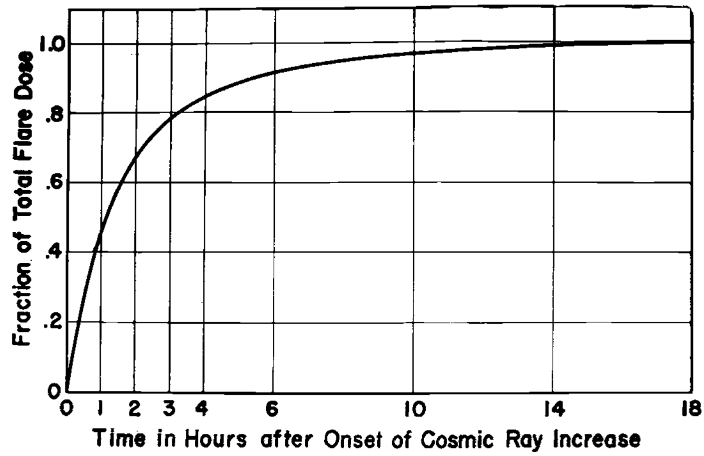


Fig. 5. Accumulation of Integral Extra-Atmospheric Flare Dose During and After Giant Solar Flare of February 23, 1956.

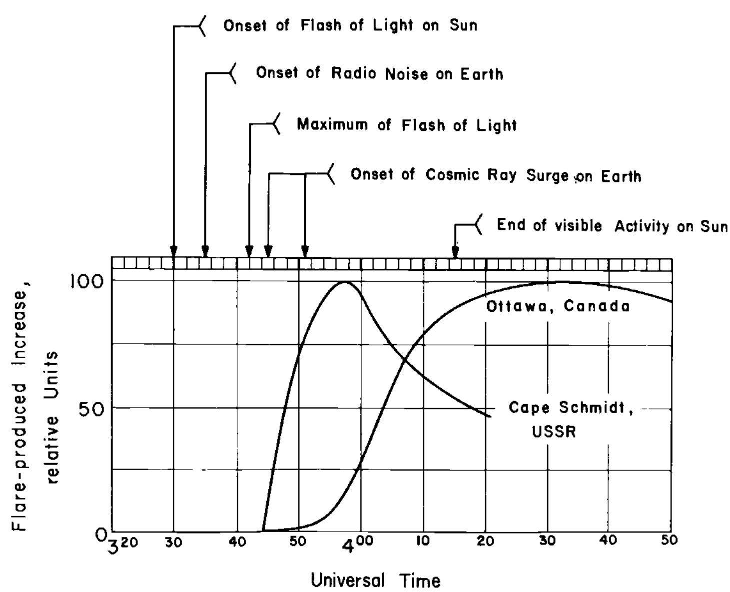


Fig. 6. Sequence of Events and Surge of "Cosmic Ray" Intensity for Giant Solar Flare of February 23, 1956. Note slower onset and longer protraction of surge on night side of earth (Ottawa).

dose is encountered again. These aspects have been discussed elsewhere.[5] It has been shown that the intratarget dosage distribution for pro-

The radiation hazard presents itself indeed as a major obstacle for man's venture into space. The particular challenge rests in the unpredictability and the everchanging conditions with regard to time and location of high intensity proton fluxes. While for an earth-circling satellite it seems safe to state that the radiation hazard will not be an insurmountable impasse, quite serious doubts must be voiced as far as manned missions deeper into space are concerned.

SUMMARY

Twelve years after the discovery of the heavy nuclei of primary cosmic radiation, the mode of action of this type of densely ionizing radiation on living matter is still essentially unknown. Inferences from other radiations with a high rate of energy dissipation have not been conclusive heretofore because the micro-structure of the ionization columns differs too much from that of cosmic ray heavy primaries. A first break in this deadlock seems accomplished by the recently reached energy levels of the HILAC (Heavy Ion Linear Accelerator). A detailed analysis of the diameter of the ionization column of HILAC Argon tracks shows that the large radial spread of cosmic ray heavy nuclei is for the first time well simulated by a laboratory source. Though with regard to the depth of penetration still much seems left to be desired, the basic question of the microbeam effectiveness of heavy nuclei seems now accessible to laboratory studies.

The discussion of radiation hazards in space flight centers at present upon the newly discovered proton radiation fields of various origin in space. The greatly enhanced proton flux during and after large solar flares is of special concern. It seems of interest to investigate the time reserve that exists for re-entry behind the shield of the atmosphere after the onset of a large flare on the sun. Comparing the time of flight for a typical flare-produced proton spectrum to the speed of light and studying the data on the impact zones for the giant solar flare of February 23, 1956, shows that the grace period is of the order of fifteen to forty minutes. It depends in a complex manner on latitude and longitude of position relative to the sun and on the compromise of how much of the initial steep surge of the extra-atmospheric radiation intensity one wants to accept.

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## "The Dark Fence": Radar Screen Detects Orbiting Objects

The Navy has announced that the so-called "dark fence" will be completed later this year. It has been in partial operation for some months.

The screen will be created by a 500,000-watt transmitter (three smaller transmitters are now in operation) emitting a broad, thin radio curtain across the continent from southern California to Georgia. Reflections of objects in near space are picked up by gigantic receiver arrays. Data are fed into computers, and the orbits can be calculated. The system makes it possible to detect and track nonradiating satellites passing over this country. Navy officials said that even in its present partially completed form the system has detected and tracked a piece of wire 15 feet long orbiting at a height of 400 miles. The wire was debris from U. S. satellite.—*Science*, March 3, 1961.