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Protons and Space Travel—An Introduction[1]

GLENN V. DALRYMPLE[2] AND IAN R. LINDSAY[3]

USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas

INTRODUCTION

With the launching of the first artificial satellite less than ten years ago, man started toward the penetration of deep space. The balloon and satellite flights which followed this initial venture have yielded valuable information about the nature of the hostile space environment. These deeply penetrating space probes showed conclusively that one of the significant hazards facing the space traveler is ionizing radiation. Fortunately, the early manned flights were not disturbed by high radiation fields because they were made at relatively low altitudes. As progressively longer space flights are made, however, the probability increases that the occupants of the vehicles will receive larger doses of radiation. Because of this situation, the necessity for learning about the biological effects of protons has emerged.

THE SPACE RADIATION ENVIRONMENT

Since many detailed reviews of the physical makeup of the space radiation environment have been published during the past few years (*1–4*), we give only a brief summary. Generally, the radiations found in space can be grouped into four major categories: (1) electromagnetic radiations, (2) electrons, (3) protons, and (4) nuclei of elements with atomic number (Z number) greater than 1. The electrons and electromagnetic radiations have sufficiently low energy (and subsequently low penetration power) that they do not represent a great hazard to the occupant of the vehicle as long as he remains inside, because the shielding provided by the vehicle walls would be thick enough to absorb these radiations. The protons and heavier nuclei, however, do represent a very real danger because a large number of them have sufficient energy to penetrate the thickest shielding, either available now or planned for years to come. Of these particles, the protons are by far the most hazardous to the space traveler because of the weight of their numbers. Of all

[1] Task No. 775704, funded by the National Aeronautics and Space Administration.

[2] Captain, USAF, MC. Presently Assistant Professor of Radiology, University of Arkansas Medical Center, Little Rock, Arkansas.

[3] Wing Commander, RAF.

charged particles (excluding electrons) found in space, the protons make up well over 90% of the total (*1*).

Geographically, the naturally occurring radiations of space may be grossly subdivided into three categories: (1) geomagnetically trapped particles (Van Allen zones), (2) galactic cosmic radiations, and (3) solar radiations. The inner Van Allen zone is located 600 to 10,000 km from the surface of the earth and is concentrated over the magnetic equator. Electrons, protons, and the nuclei of light elements (lithium and helium) make up the majority of radiations found in this region. The electrons are the most prevalent—more than 99% of all particles. The protons represent less than 0.1% of all particles, and the heavier nuclei are much less abundant than the protons. Since the electrons have, at most, energies of a few million electron volts, they do not have sufficient energy to penetrate the walls of a space vehicle and present a hazard. Bremsstrahlung produced by interaction of electrons with the shielding material may represent a danger, however. Since a significant fraction of the protons have sufficient energy to penetrate the capsule, the occupants may be subjected to radiation fields of 10 to 20 rads/hour while in the inner zone (*5*). This dose rate could go even higher during a solar flare. The outer Van Allen zone is considerably larger than the inner zone; it is located about 15,000 to 70,000 km from the surface of the earth. Electrons make up the majority of particles of this zone. While protons are also represented, they are by several orders of magnitude less numerous than in the inner zone.

The galactic cosmic radiations are believed to originate outside our solar system but within our galaxy. Approximately 86% are protons, 13% are α-particles, and the remaining 1% is made up of elements of higher Z (*1*). These radiations may have energies up to 10^{18} ev, which means that thicknesses of material approaching the radius of the earth are necessary to stop the most energetic of them. While many of these particles have very high energies, the total number is low. According to current estimates, these radiations will probably provide doses of the order of 0.6 mR/hour behind 1 gm of low-Z shielding per square centimeter, which should not be of great significance *per se* for short voyages, but which could become serious for voyages of several years' duration (*6*).

The very-high-energy particles may also provide a hazard from a different source. When these particles traverse tissues, they are capable of hitting nuclei of the atoms present and creating "stars," which are events in which large amounts of energy are liberated in a relatively small volume. During this process, radiations of high linear energy transfer (LET) and high relative biological effectiveness (RBE) are emitted. Although the total number of these events would be small, the possibility of some catastrophe, occurring in a critical biological control system (such as the respiratory or the cardiac centers of the brain) is of great interest, since we shall never be able to provide enough shielding to stop all these high-energy particles (*7*, *8*).

The solar radiations are extremely variable with regard to time of occurrence and distribution of energy. A large number of particles (primarily protons and electrons) are given off from the sun in the form of the solar plasma (wind). These particle energies are low (electron energies are in the electron volt region, and the protons have less than 5 Mev of energy), and they do not represent a hazard to the occupants of a space vehicle.

The solar flare carries much greater biological significance. These are periods of release of large quantities of energy from the surface of the sun. A typical flare has two components (*1*). First, a burst of very-high-energy particles is ejected away from the sun in all directions; most of the particles are protons. During the approach of the high-energy particles toward the earth, they are thought to create a magnetic channel which conducts the second phase, a lower-energy plasma. The first, or high-energy, phase moves at a velocity of about 60% of the speed of light, while the plasma moves considerably more slowly. While analyses of measurements from typical flares give a wide range of dose estimates, doses from the proton component of solar flares of the order of 150 rads are believed to be possible for space voyages projected for the near future (*1*).

PROTONS

Protons and other charged particles deposit their energy while passing through tissue or other absorbers in a manner somewhat different from that of X- and γ-radiations (*9, 10*). Instead of a more or less exponential decrement of dose with depth in the absorber (as is seen with the electromagnetic radiations), protons and other charged particles give up increasingly more energy as they decelerate and approach the end of the path. Within the last few percent of the path length, the deposition of energy per unit of path length is several times as great as that at the beginning of the path. Therefore, instead of having a radiation which provides the irradiated material with about the same LET (and RBE) throughout the irradiated volume, as is the case with X- and γ-radiation (*11*), the protons can produce more than a hundredfold change in LET, depending on the proximity of the reference point to the end of the path. Therefore, the protons produce a very complex distribution of doses and LET's throughout the depth of the irradiated subject.

In addition to the pattern of energy deposition from the protons, the interaction of the protons with matter is generally more complex than that produced by the familiar electromagnetic radiations. At energies used for most radiobiological research, the electromagnetic radiations interact with the absorbing medium primarily by Compton scattering. Protons not only cause ionization by a similar mechanism (primaries, dE/dx energy losses); they also interact with the nuclei of the target material and produce a wide variety of reaction products (secondaries) such as evaporation nucleons, and recoil nuclei (*12*). The result is that the total deposition of energy by the protons is indeed very involved.

The protons, as found in space, provide still another complexity. These protons

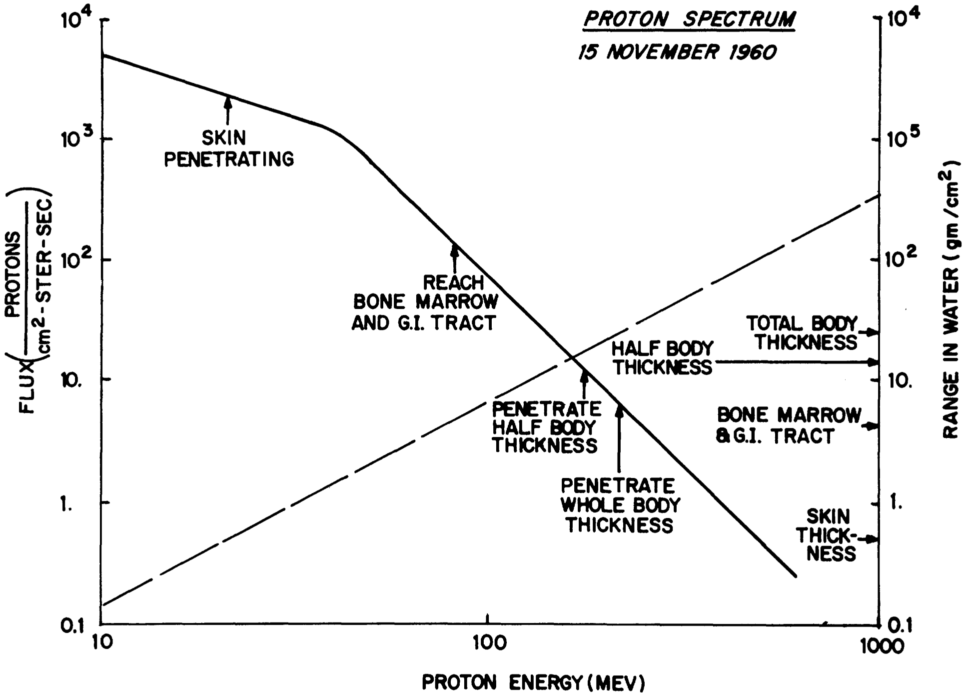

FIG. 1. The solid line gives the proton spectrum measured November 15, 1960 (*15*). The dashed line indicates the range of the protons as a function of energy. The depths of several radiosensitive structures in an adult man are indicated.

do not exist as simple monoenergetic sources; rather they are found in complex spectra (see Fig. 1) of energies and intensities. This figure shows a spectrum which was measured on November 15, 1960 (*13*). There are many protons in the range 10 Mev $\leqq E \leqq$ 100 Mev, but relatively few in the range 100 Mev $\leqq E \leqq$ 1000 Mev. This figure represents an idealized spectrum; actually, the spectrum continuously changes. Also, when extensive solar flare activity is present, the absolute number of protons may increase severalfold.

THE BIOLOGICAL PROBLEM

Because of the presence of the radiation hazard due to the protons, a knowledge of their biological effects must be available before man can penetrate deep space with even marginal safety. Unfortunately, the amount of information about the biological effects of protons and heavier charged particles is very small. Most of the work has been concerned with effects produced in cellular systems such as bacteria and tissue culture cells (*14*). The literature dealing with the biological effects in small animals such as rats and mice is limited and contains primarily mortality results.

With one exception, no information is available about the effects produced by total-body proton irradiation of large animals (*15*).

This paucity of data is not due to any lack of interest among the experimentalists. Rather, it stems from the difficulty in obtaining enough time on the very few available (and appropriate) cyclotrons and large accelerators to perform even the most basic biological studies.

Even with sufficient accelerator time to perform experiments, the problem of depth-dose distribution from the space proton spectrum must be carefully considered. In addition to the proton spectrum, the range in tissues of the protons as a function of energy is plotted in Fig. 1. Also entered in the figure are the approximate depths at which several radiosensitive structures are located. It is immediately apparent that the skin receives several times as much dose as the deeper bone marrow and gastrointestinal tract. Also, the more superficial structures are irradiated with protons delivered at a higher dose rate.

At least two basic experimental avenues are available for studying the effects of these protons. The first, and most direct, would be to simulate the space proton spectrum under laboratory conditions and then to irradiate animals with these protons. Unfortunately, this task is difficult from a technical standpoint, not only because of the complex distribution of proton energies and intensities, but also because only a very few cyclotrons are available that have the capability to perform such studies.

A second approach would be to use monoenergetic sources of protons, with the energies being selected to represent important portions of the solar proton spectrum. After an understanding is gained of the exposure of animals to discrete proton energies, an estimate of the combined effect of the proton spectrum could be made. We chose this latter approach because it allows the use of existing (and available) cyclotrons without great amounts of modification.

The experiments described in the papers to follow were performed at three cyclotron facilities. The Oak Ridge Isochronous Cyclotron (ORIC) was used for 32-Mev and 55-Mev proton irradiations; the Harvard University Synchro-cyclotron was the source of 138-Mev protons; and the University of Chicago Cyclotron provided 250-Mev and 400-Mev protons. These energies were chosen to represent significant portions of the proton spectrum as applied to both man and the small primates (*Macaca mulatta*) used for most of the experiments. This primate has an average cross-sectional diameter of about 10 cm and a body configuration similar to man's. Since the 32-Mev and 55-Mev protons have a range of 1 cm and 2.6 cm in tissue, respectively, even rotational exposure techniques will not provide irradiation of the total body volume.

The 32-Mev protons do not have sufficient range to reach the radiosensitive bone marrow and gastrointestinal tract. Therefore, studies with these protons give information about the response of the skin and subcutaneous tissue in the absence of bone marrow and gastrointestinal injury. The 55-Mev protons provide exposure of additional tissue. Although the range of these protons is sufficient to allow irradiation of a sizable portion of the bone marrow and the gastrointestinal tract, approximately 25% of the total body volume would not be reached.

The 138-Mev protons have enough range in tissue to irradiate homogeneously the total body volume. The primary mode of energy deposition by these protons is interaction with the orbital electrons (dE/dx energy losses); this mode is analogous to the familiar Compton scattering produced by X- and γ-radiation. Nuclear processes would constitute less than 10% of the total dose (*12*).

While the 250-Mev and 400-Mev protons also have sufficient range in tissue to provide a homogeneous depth-dose distribution, the increasing proton energy is associated with a relatively greater contribution of nuclear processes to the total dose. It should be recalled that many of these nuclear processes produce radiations of high LET and high RBE (*12*).

The proton energies (32, 55, 138, 250, and 400 Mev) explored in the papers to follow certainly represent significant portions of the space radiation spectrum (see Fig. 1). Since the 32-Mev and 55-Mev protons do not penetrate the entire body thickness, they provide an inhomogeneous dose distribution in the *Macaca mulatta*. The higher energies, while producing a homogeneous dose distribution, produce increasingly greater numbers of the high-LET secondaries. Also, the 400-Mev energy is about the maximum found in the space proton spectrum (except for the few very-high-energy galactic cosmic particles). The effects of the discrete proton energies will be examined in detail, and from these results an estimate of the biological effects of the complex space proton spectrum will be made.

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REFERENCES

1. R. WALLACE, *Advan. Biol. Med. Phys.* **8,** 354–374 (1962).

2. D. L. DYE and M. WILKINSON, Radiation hazards in space. *Science* **147,** 19–25 (1965).

3. H. E. NEWELL and J. E. NAUGLE, Radiation environment in space. *Science* **132,** 1465–1472 (1960).

4. W. H. LANGHAM, P. M. BROOKS, AND D. GRAHAM, Radiation biology and space environment parameters. *Aerospace Med.* **36,** 55 pps. (1965).

5. C. A. TOBIAS, Radiation and life in space. *Federation Proc.* **18,** 1242–1249 (1959).

6. J. R. WINKLER, Primary cosmic rays, *Radiation Res.* **14,** 521–539 (1961).

7. H. J. SCHAEFFER, "Air" dose, tissue dose, and depth dose of the cosmic ray beam in the atmosphere. *Radiation Res.* **9,** 59–76 (1958).

8. H. J. CURTIS, Limitations on space flight due to cosmic radiations. *Science* **133,** 312–316 (1961).

9. W. H. BRAGG and R. D. KLEEMAN, On the α particles of radium and their loss of range in passing through various atoms and molecules. *Phil. Mag.* **10,** 318 (1905).

10. A. C. BIRGE, H. O. ANGER, and C. A. TOBIAS, Heavy charged particle beams. In *Radiation Dosimetry* (G. J. Hine and G. L. Brownell, eds.), p. 624, Academic Press, New York, 1956.

11. J. S. KROHMER, RBE and quality of electromagnetic radiation at depths in a water phantom. *Radiation Res.* **24**, 547–562 (1965).
12. J. E. TURNER, C. D. ZERBY, R. L. WOODYARD, H. A. WRIGHT, W. E. KINNEY, W. S. SNYDER, and J. NEUFELD, Calculation of radiation dose from protons to 400 Mev. *Health Phys.* **10**, 783–808 (1964).
13. F. B. MCDONALD (ed.), Solar proton manual. NASA Technical Report NASA TR R-169, 117 pps. (1963).
14. C. A. TOBIAS and T. BUSTAD, Radiobiological studies with accelerated heavy ions. Second International Symposium on Physics and Medicine of the Atmosphere and Space, November 1958.
15. J. E. PICKERING, Biological effects of whole-body proton irradiation. *Aerospace Med.* **34**, 942–943 (1963).