4. G. M. Smith and D. C. Regnery, *Proc. Natl. Acad. Sci. U.S.* **36**, 246 (1950).
5. R. Sager, *Genetics* **40**, 476 (1955).
6. W. T. Ebersold and R. P. Levine, *Z. Vererbungsl.* **90**, 74 (1959).
7. R. Sager, *Proc. Natl. Acad. Sci. U.S.* **40**, 356 (1954).
8. ——— and Y. Tsubo, *Bacteriol. Proc. (Soc. Am. Bacteriologists)* **60**, 184 (1960); ———, in preparation.
9. The recrystallized streptomycin and streptomycin-$C^{14}$ used in this study were the gift of Merck and Company.
10. R. Sager, unpublished results.
11. W. Szybalski and S. Mashima, *Biochem. Biophys. Research Communs.* **1**, 249 (1959); N. Anand and B. D. Davis, *Nature* **185**, 22 (1960).
12. F. Jacob, P. Schaeffer, E. L. Wollman, in *Microbial Genetics* (Proc. Society for General Microbiology, 10th Symposium), W. Hayes and R. C. Clowes, Eds. (Cambridge Univ. Press, New York, 1960), p. 67.
13. M. Delbruck, in *Unites biologiques douées de continuité genetique* (Paris, 1949), p. 33.
14. M. R. Pollock, in *Adaptation in Microorganisms* (Proc. Society for General Microbiology, 3rd Symposium), E. F. Gale and R. Davies, Eds. (Cambridge Univ. Press, New York, 1953), p. 150.
15. D. E. Catcheside, *Nature* **184**, 1012 (1959).
16. H. Von Euler, M. Bracco, L. Heller, *Compt. rend.* **227**, 16 (1948).
17. L. Provasoli, S. H. Hutner, I. J. Pintner, *Cold Spring Harbor Symposia Quant. Biol.* **16**, 113 (1951).
18. R. Sager and Y. Tsubo, Proc. 3rd Intern. Congr. Photobiol., Copenhagen, 1960, in press; Y. Tsubo and R. Sager, in preparation.
19. This work was supported by grants from the U.S. Public Health Service and the National Science Foundation.

# Radiation Environment in Space

Satellites and space probes are revealing the kinds and amounts of radiation men will encounter in space.

Homer E. Newell and John E. Naugle

That vast region beyond the earth's atmosphere often referred to as the void of outer space is not really empty. Through interplanetary space there stream electromagnetic radiations of all wavelengths, electrons, protons, and other nuclei, including cosmic rays, and aggregate particles called micrometeorites. In fact, many of the fundamental particles and quantum radiations have already been observed, and, doubtless, all will be eventually.

Within the solar system, the sun is the primary source of both electromagnetic radiations and particle radiations. In addition to the visible wavelengths which pour forth continuously from the sun, there are ultraviolet and x-ray radiations of variable intensity. At times of great solar activity clouds of electrons and protons are spewed forth and sweep through the regions of interplanetary space. It even appears likely that the sun may contribute to the cosmic radiation.

Before May 1958, radiation was not considered a serious hazard to space travel. Little was feared from the electromagnetic radiations to be encountered. Most of the wavelengths would be in the visible regions, and it was expected that the ultraviolet and x-ray intensities would be low enough to cause no concern. Rocket observations bore out this conclusion. Moreover, the available experimental data indicated that the only particle radiations in space would be cosmic rays, and that the radiation level due to cosmic rays would be negligible for most space missions.

However, on 1 May 1958, James A. Van Allen announced the discovery of the great radiation belts around the earth. The radiation levels in these belts are not negligible. A second phenomenon, the so-called solar proton beams, or solar cosmic rays, was discovered shortly thereafter. Thus, in the course of a few months radiation changed from an unimportant factor in space travel to a major factor affecting the choice of trajectories and determining the size and weight of the spacecraft and their physical configuration.

In this article we summarize some of the information on radiations in space obtained by means of satellites and space probes. The physical nature of these radiations is discussed, together with the mechanism by which the radiation interacts with matter. Dosage levels are defined. The salient factors in the choice of shielding are given. Finally, an attempt is made to assess the importance of radiations in space to various space missions, such as Project Mercury, circumlunar flights, and the operation of unmanned satellites and space probes.

## Electromagnetic Radiations

As stated above, the electromagnetic radiations encountered in interplanetary space are primarily solar in origin. At a distance of one astronomical unit from the sun, the total energy flux in this solar radiation amounts to about 2 calories per square centimeter per minute, which is equivalent to 0.14 watt per square centimeter. The radiation is mostly in the visible wavelengths. About 7 percent of the total energy flux lies in the ultraviolet regions between 2000 and 4000 angstroms; in still shorter wavelengths in the vicinity of the Lyman-alpha line of hydrogen, 1216 A, the total intensity is down by many orders of magnitude, averaging about $6 \times 10^{-7}$ watt/cm$^2$. In the soft x-ray wavelengths intensities fall off another order of magnitude or more. Occasionally harder x-rays are observed at the time of the solar flares. Gamma radiation is normally of negligibly small intensity.

Rocket observations by the Naval Research Laboratory group have revealed ultraviolet fluxes from distant astronomical sources. Moreover, the hydrogen in interstellar and interplanetary space is a source of some radiation in the Lyman-alpha wavelengths.

The intensity of the solar radiations

Dr. Newell is deputy director of space flight programs, National Aeronautics and Space Administration, Washington, D.C., and Dr. Naugle is head of energetic particles at NASA. This article is based on a paper presented on 13 Oct. 1960 at the third astronautic symposium of the Air Force Office of Scientific Research, held in conjunction with the national aeronautics meeting of the Society of Automotive Engineers, Los Angeles, Calif.

will vary inversely as the square of the distance from the sun. Thus, at the distance of Venus from the sun the total solar energy flux may be expected to be about twice that at the earth's distance, or 0.28 watt/cm$^2$. At the distance of Mars this figure would become 0.06 watt/cm$^2$.

In the vicinity of a planet, a satellite or spacecraft would also be subject to radiation from the planet itself. Much of this radiation will be in the infrared. In the case of the earth, this amounts to about 0.06 watt/cm$^2$ on the average. In addition, the planet reflects incoming solar radiation in amounts determined by the planetary albedo, which for the earth is 0.4. Within the shadow cast by the planet, the solar radiation is, of course, cut off.

In general, it does not appear that electromagnetic radiations within the solar system present a serious hazard to space flight, until close approaches to the sun are made. It is possible with very little effort to provide shielding from the different radiations. It is a matter of straightforward engineering to provide adequate cooling for equipment and living occupants of satellite stations or spacecraft. Under the action of the shorter wavelengths, certain materials, such as plastics, may be expected to undergo long-term changes in properties. If such changes have an adverse effect for the use to which such materials are being put, then either protection must be provided or substitute materials must be found. But none of these problems should furnish any deterrent at all to space operations and space flight.

## Cosmic Rays

The cosmic radiation contains the most energetic particles known. Energies of individual particles range from a few million to $10^{19}$ electron volts. The primary radiation found in interplanetary space consists of protons, alpha particles, and the nuclei of heavier elements up to at least iron. The protons comprise roughly 86 percent of the radiation, 13 percent is accounted for by the alpha particles, and the remaining 1 percent consists of the heavier particles. Away from the earth in interplanetary space, the total intensity is about two particles per square centimeter per second from all directions. In the vicinity of the earth, this intensity is divided by two, due to the shielding effect of the earth itself.

Near a planet containing an atmosphere one may expect an additional component to the cosmic radiation caused by back scatter of secondary particles, due to collisions of the primaries with the atmospheric molecules. For the earth this albedo, as it is often called, has been observed and measured. This albedo consists of neutrons, mesons, and various decay products of these particles. The intensity is sufficiently great to suggest that the cosmic ray albedo is the source of some of the radiation trapped in the Van Allen radiation belt, particularly in the inner zone.

As measured at the earth, the cosmic ray flux varies by a factor of two during the 11-year solar cycle, with the maximum cosmic ray flux occurring at the time of minimum solar activity. Table 1 gives the fluxes of the particles in the cosmic radiation and their relative abundance. These figures are obtained by extrapolating fluxes measured at balloon altitudes to the top of the atmosphere. The value for the total flux is that measured in satellites and deep space probes.

Figure 1 shows the variation of the cosmic ray flux with energy. Figure 2 shows the manner in which cosmic rays interact with the nuclei of the atmosphere to produce secondaries. Figure 3 shows the effect of the earth's magnetic field on a very low energy, a medium-energy, and a high-energy cosmic ray.

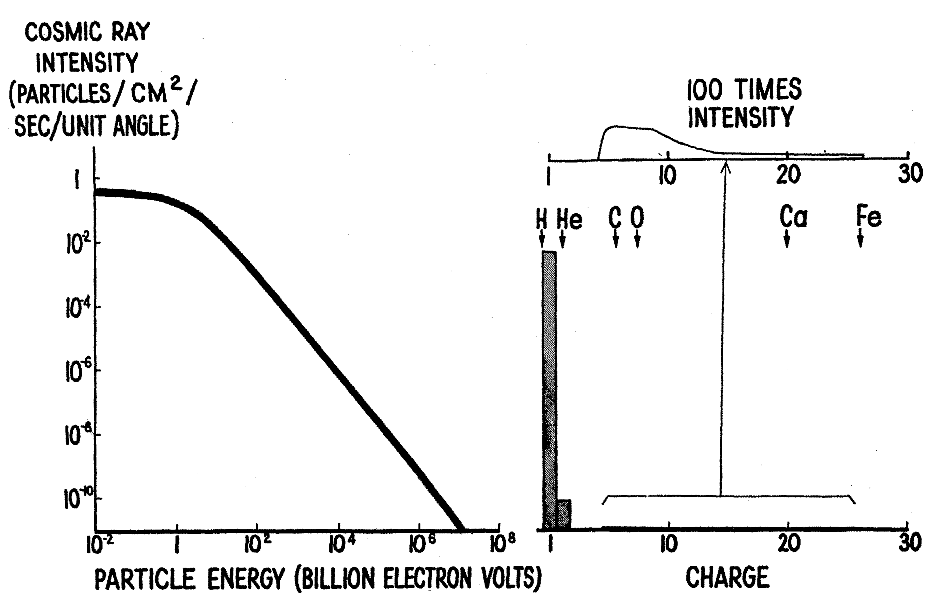


Fig. 1. Cosmic ray energy and charge spectrum.

## Trapped Radiation

The first Explorer satellite led to the discovery by Van Allen and his colleagues of the belt of high-energy particle radiations surrounding the earth. Since its discovery the radiation belt has been investigated in the United States with the Explorer satellites and Pioneer probes, and in the U.S.S.R. with the Sputniks and Soviet space probes.

It has become clear that the earth's radiation belt consists of charged particles trapped by the earth's magnetic field, as shown in Fig. 4. The particles travel in spiral paths along the magnetic line of force from pole to pole. As a particle moves toward a pole the pitch angle between the particle's path and the direction of the magnetic field becomes greater and greater, until finally it reaches 90°. At this point the particle is reflected and begins to spiral back along the same line of force. Thus the particle travels back and forth until collisions with atmospheric molecules or other effects remove it from the radiation belt.

It seems clear that any planet possessing a magnetic field of sufficient strength will also exhibit a radiation belt similar to that of the earth. Thus the problems in space flight introduced by the earth's radiation belt may be expected to be encountered again in the case of flights in the vicinity of other planets.

As shown in Fig. 4, the earth's radiation belt appears to consist of at least two separate regions. Both zones contain appreciable numbers of electrons ranging in energy from 20,000 electron volts to several times $10^5$ ev or more. In the outer zone, the electron flux is a couple of orders of magnitude greater than in the inner re-

Table 1. Flux and relative abundances of particles in cosmic radiation. Fluxes are measured in balloons and extrapolated to the top of the atmosphere. Interplanetary flux is that measured on Pioneer IV.

| Type of particle | Flux (particle $cm^{-2}$ $sec^{-1}$ $ster^{-1}$) | Relative abundance (%) |
|---|---|---|
| Electrons ($E \geqq$ 30 Mev) (*6*) | — | <1 |
| Protons ($E \geqq$ 280 Mev) (*7*) | 0.095 | 86 |
| Alphas ($E \geqq$ 160 Mev/nucleon) | .015 | 13 |
| $3 \leqq Z$ ($E \geqq$ 360 Mev/nucleon) (*8*) | .0014 | 1 |
| Total from balloons | .111 | 100 |
| Interplanetary flux | .14 | 100 |
| (Protons, $E \geqq$ 30 Mev) (Electrons, $E \geqq$ 2 Mev) | | |

gion. The inner region, on the other hand, is characterized by the presence of high-energy protons, which are not detected in the outer region.

Because the dipole field of the earth is offset from the center of the earth by 360 kilometers, there is a longitudinal variation in the lower edge of the radiation belt. The altitude of the lower edge of the inner belt is as low as 460 km over Santiago, Chile, and as high as 1480 km over Australia.

The particles trapped in the radiation belt are found in appreciable quantities at altitudes above 1000 km over the equator, and above 300 km in northern latitudes. Over the equator, the maximum intensity of the inner zone appears at somewhat less than 4000 km, while the maximum of the outer zone appears at about 16,000 km. Van Allen's estimates of the particle fluxes at the inner zone and outer zone maxima are given in Table 2. The outer zone extends out into space to a distance of around 55,000 km.

The inner zone of the radiation belt appears to be remarkably stable, showing very little variation with solar activity. In contrast, the outer zone fluctuates in radiation intensity and spatial extent. These fluctuations are directly associated with solar activity. Results from the Iowa, Chicago, and Minnesota groups obtained by means of Explorer satellites and Pioneer V provide some detail on this variation in the content and extent of the radiation belt. It has been found that, at the onset of a magnetic storm, the radiation intensity in the outer zone falls rapidly to a very low value. Simultaneously auroral displays in the earth's atmosphere appear. There then follows a rapid recovery in intensity which may build up to more than the prestorm level. Thereafter there is a gradual decline to the prestorm level.

## Particle Radiation in Interplanetary Space

In addition to the cosmic radiation already discussed, interplanetary space contains the lower-energy particle radiation emitted by the sun. This radiation has not yet been observed in sufficient detail to determine fully its character. The instruments so far flown on deep space probes were incapable of recording particles of energy lower than 2 Mev for protons or 20 kev for electrons. Except at times of high solar activity the instruments recorded essentially the normal cosmic ray background intensity. Even at times of high solar activity the electron intensities were never as great as those observed in the radiation belt. A direct conclusion has been that the higher-energy electrons found in the radiation belt have acquired their energy by some local acceleration mechanism in the vicinity of the earth. The details of this mechanism have not yet been determined.

Thirty times in the past three years beams of protons have been detected over the polar regions following a large solar flare on the sun. These proton beams begin bombarding the polar caps of the earth approximately 1 hour

Table 2. Van Allen's estimates on particle flux (*9*).

*Heart of inner zone*
(3600 km on geomagnetic equator)

(*a*) Electrons, $E > 20$ kev: maximum unidirectional intensity: $\sim 2 \times 10^9$ $cm^{-2}$ $sec^{-1}$ $ster^{-1}$

(*b*) Electrons, $E > 600$ kev: maximum unidirectional intensity: $\sim 1 \times 10^7$ $cm^{-2}$ $sec^{-1}$ $ster^{-1}$

(*c*) Protons, $E > 40$ Mev: maximum omnidirectional intensity: $\sim 2 \times 10^4$ $cm^{-2}$ $sec^{-1}$

*Heart of outer zone*
(16,000 km on geomagnetic equator)

(*a*) Electrons, $E > 20$ kev: omnidirectional intensity: $\sim 1 \times 10^{11}$ $cm^{-2}$ $sec^{-1}$

(*b*) Electrons, $E > 200$ kev omnidirectional intensity: $1 \times 10^8$ $cm^{-2}$ $sec^{-1}$

(*c*) Protons, $E \sim 60$ Mev: omnidirectional intensity: $\sim < 10^2$ $cm^{-2}$ $sec^{-1}$

(*d*) Protons, $E < 30$ Mev: no information

after a flare of importance 2+ or greater has occurred on the sun. Not all flares of this magnitude, however, eject protons. The high flux may last from 10 to 100 hours. Of the 30 events so far observed, six were of such intensity and duration as to have given a lethal dose to an unprotected person in free space. Intensities of $5 \times 10^6$ protons per square centimeter per second for free space have been inferred by extrapolating balloon data to the top of the atmosphere.

Usually the number of particles decreases very fast as their energy increases. Thus a small amount of shielding causes a marked decrease in the dose rate. However, on at least one occasion a flat energy spectrum has been observed. The energy of the protons

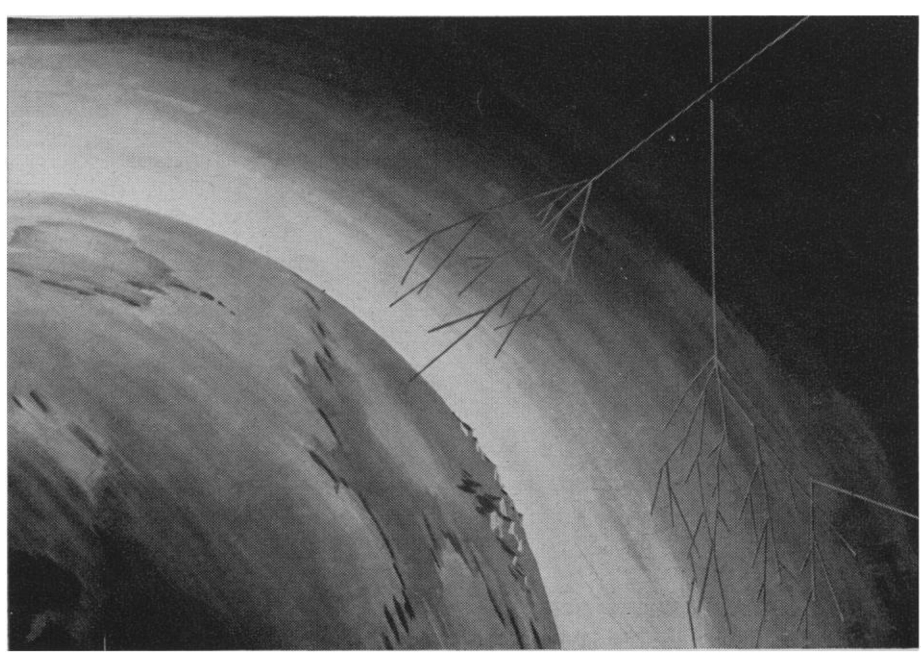

Fig. 2. Cosmic ray interactions with the earth's atmosphere.

varies from a few million electron volts to 700 Mev.

The frequency of these events varies over the 11-year cycle of solar activity. We have just passed through an extremely active period in which there was an average of ten per year. We are entering a period in which there will be at most perhaps one or two per year. The next period of high solar activity will begin in 1967.

The solar proton events are one of the major problems in the design of manned space vehicles. In the first place, their occurrence is presently unpredictable. In the second place, the magnitude and duration of the radiation level is also unpredictable.

## Nature of the Radiation

Having discussed what radiations are encountered in interplanetary space and in the vicinity of the earth, let us now consider their fundamental nature. As stated earlier, all of the fundamental particles and quantum radiations, with the exception of the short-lived mesons, have been found in space. Table 3 shows the various kinds of particles and quantum radiations of particular importance. The electron and proton are both charged particles and along with the neutron form the three fundamental particles used to build ordinary atoms and molecules. The neutron flux in free space has not been measured, but it should be extremely small. The neutron lives only about 15 minutes, which limits the distance it can travel from its point of origin. The neutron spontaneously decays into a proton and an electron, both of which are stable particles. Gamma rays and x-rays are both high-frequency electromagnetic radiation. Gamma rays have the higher frequency, and since the amount of energy, the so-called photon or quantum of energy, which can be transferred to matter is proportional to the frequency, gamma rays have the higher energy. The exact energy which divides photons into x-rays or gamma rays varies, but generally it is taken as 1 Mev. Photons of energy $>1$ Mev are called gamma rays. They result from nuclear interactions and the so-called bremsstrahlung of electrons. X-rays are more easily absorbed and are produced primarily by electron bremsstrahlung. The heavier positively charged particles are found in cosmic rays. They penetrate into the atmosphere, down to about 80,000 feet, where they slow down and pick up a number of electrons equal to their charge and become ordinary neutral atoms.

## Nature of the Interaction between Radiation and Matter

Radiation damage is done almost entirely by charged particles. As a charged particle travels through matter it exerts a force on electrons in the surrounding medium; the electrons move and thereby take up energy from the traversing particles. This process is called ionization because the removal of the electrons leaves positively and negatively charged ions in the surrounding medium. Neutral radiation, such as neutrons or photons, causes damage by first interacting with a charged particle, giving it sufficient energy to produce ionization. Large numbers of electrons are produced. A proton will liberate from $10^5$ to $10^6$ electrons per centimeter of path length in water.

The rate of ionization is proportional to the square of the charge on the particle and is inversely proportional to the square of its velocity. The rate of energy loss varies somewhat with the material through which the particle is traveling. This will be discussed in greater detail when we discuss shielding.

In addition to losing energy by ionization, an electron when decelerated will radiate gamma rays or soft x-rays. A proton of a given energy has a cor-

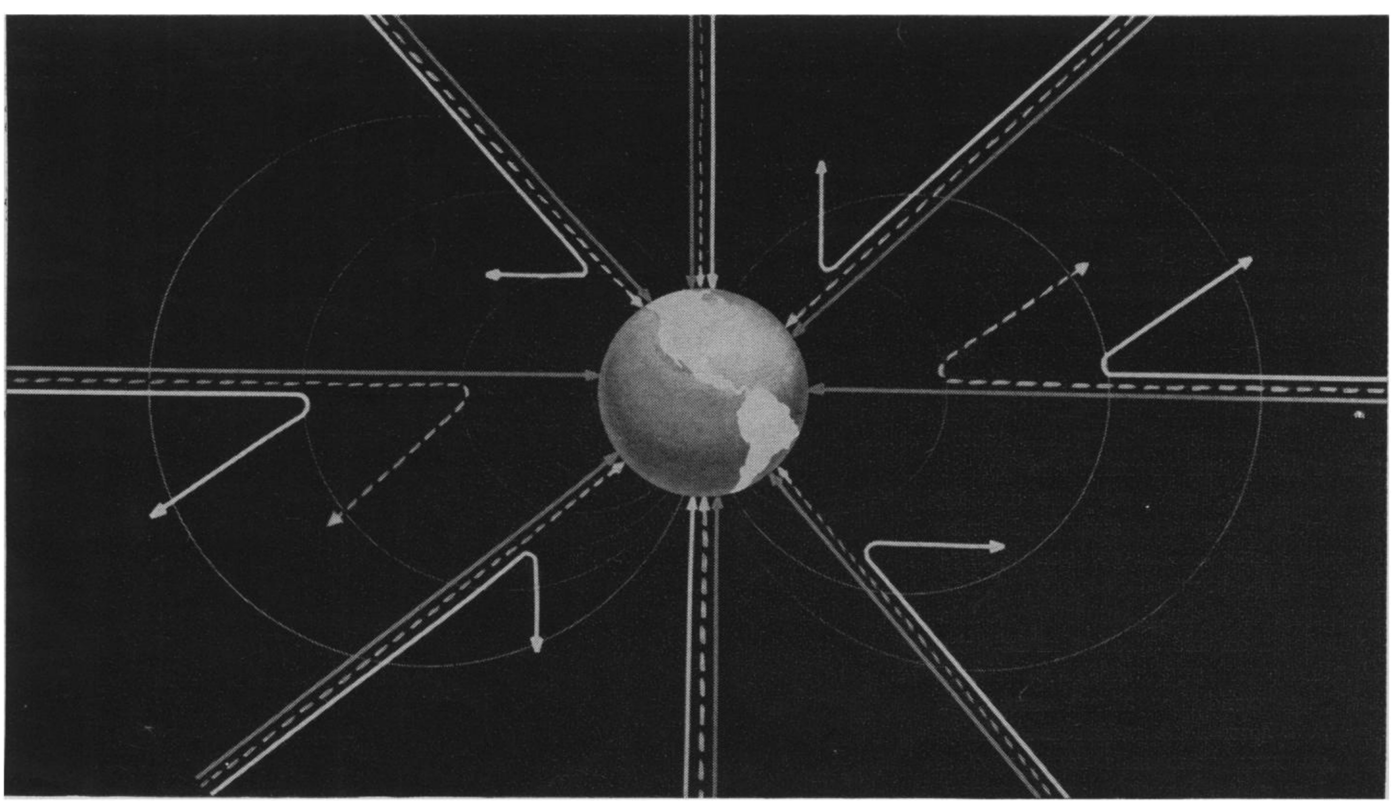

Fig. 3. Effect of latitude and altitude on cosmic ray intensity.

responding well-defined range in a given material. One gram of aluminum will stop a beam of 2.3-Mev electrons or a beam of 35-Mev protons. However, in the case of the protons a negligible amount of radiation would penetrate more than the 1 gram of aluminum, whereas for the electron a large amount of x-ray and gamma ray radiation that is produced would penetrate another 10 to 12 grams of aluminum. The exact mechanism by which the electrons liberated in tissue cause damage is complicated and not completely understood and will not be discussed in this article.

Table 3. Radiation in space.

| Name | Nature of radiation | Charge | Mass | Where found |
|---|---|---|---|---|
| Photon | Electromagnetic | 0 | 0 | Radiation belts, solar radiation (produced by nuclear reactions and by stopping electrons) |
| Quantum | Electromagnetic | 0 | 0 | |
| X-ray | Electromagnetic | 0 | 0 | |
| Gamma ray | Electromagnetic | 0 | 0 | |
| Electron | Particle | $-e$ | 1 $m_e$ | Radiation belt |
| Proton | Particle | $+e$ | 1840 $m_e$ or 1 amu | Cosmic rays, inner radiation belts, solar cosmic rays |
| Neutron | Particle | 0 | 1841 $m_e$ | Vicinity of planets and sun (produced in nuclear interactions—decays into proton and electron) |
| Alpha particle | Particle | $+2\ e$ | 4 amu | Cosmic rays (nucleus of helium atom) |
| Heavy primaries | Particle | $\geqq +3\ e$ | $\geqq$6 amu | Cosmic rays (nuclei of heavier atoms) |

## Radiation Dosage

The earliest measurements of radiation levels used an ionization chamber in which one applied a voltage between the outer shell and an inner electrode, thereby collecting the ions produced inside the chamber. A roentgen of radiation was that amount of radiation which would liberate one electrostatic unit of electricity in 1 cubic centimeter of air at standard pressure and temperature. Although there are later and more refined definitions of the radiation unit, we shall use only the roentgen as a measure of radiation levels. One other quantity is useful in discussing radiation; this is the so-called relative biological effectiveness, or RBE. This quantity measures the amount of damage caused by a given amount of radiation as compared to that caused by the same amount of radiation in the form of soft x-rays. For our purposes the RBE of the radiation in space can be considered as one.

Various radiation levels are given in Table 4. Twenty-five roentgens is the maximum permissible emergency dose which a man can take at one time, once in a lifetime. This is the dosage, for instance, which a man may be allowed to take to rescue an injured co-worker. After taking such a dose the man would not be permitted to take any more radiation in his lifetime.

## Radiation Hazard

We shall now attempt to evaluate the radiation hazard to be encountered in space. In doing so we shall review the various areas discussed above—namely, electromagnetic radiation, cosmic rays, trapped radiation, and the background radiation in space.

*Electromagnetic radiations.* As stated above, radiation hazards and effects due to the electromagnetic radiations normally present in outer space are expected to be virtually negligible. This includes even the x-rays and gamma rays to be encountered. The principal hazard from electromagnetic radiations may be expected from those x-rays and gamma rays generated by the interaction of charged particles with material of the satellite or spacecraft. These hazards are discussed in connection with the particle radiations themselves.

*Cosmic rays.* The radiation dosage to be expected from the cosmic radiation is given in Table 4. It is clear that the dosage is quite small. There is, however, one aspect of the radiation effects from cosmic radiation which has not been entirely evaluated. Although the over-all integrated dose from the very heavy particles is small, a very intense exposure is given to a very small amount of material along the track of the individual particle as it stops. This problem can only be studied by exposing material to cosmic rays on high-altitude and high-latitude balloon flights. Experiments are continuing, in which, at present, no one has found biological damage which can be directly attributable to heavy cosmic ray primaries.

The total dosage in space from cosmic radiation is 5 to 12 roentgens per year.

*Trapped radiation.* We have seen that the radiation trapped in the earth's magnetic field consists of protons in the energy range from a few thousand electron volts to 700 Mev, and electrons from a few electron volts to about 1 Mev. Figure 5 shows the variation of radiation dosage with altitude along the trajectories of Explorers III and IV.

Freden and White (*1*), through analysis of nuclear emulsions exposed in recoverable ICBM nose cones, have shown that the flux of protons of energy greater than $E$ is inversely proportional to $E$. This is a relatively slow fall off in flux with energy. Solar protons, for instance, fall off as the inverse 5th power of their energy (*2*).

The principal radiation hazard in the inner belt is from ionization produced by the high-energy protons. The principal radiation hazard in the outer belt is due to the soft x-rays produced as the electrons decelerate in the shell of a satellite or traversing spacecraft.

*Radiations in space.* Radiations in space consist of the cosmic rays, lower-energy electrons and other particles not yet observed by measuring instruments, and the solar proton beams of high-energy protons emitted by the sun dur-

Table 4. Maximum permissible radiation dosages and some typical exposure levels (in roentgens).

| Item | Amount |
|---|---|
| *Permissible exposures* | |
| Maximum permissible dosages | 0.3* r/quarter<br>5.0 r/yr |
| Maximum permissible emergency exposure | 25 r |
| *Typical exposures* | |
| Normal radiation level (sea level) | 0.001 r/day |
| Undisturbed interplanetary space (cosmic rays) | 5–12 r/yr |
| Heart of inner belt (protons) | 24 r/hr |
| Heart of outer belt (soft x-rays) | ~200 r/hr |
| Solar proton event (protons) | $10–10^8$ r/hr |
| Total exposure | 2–400 r |

* Limit prescribed for radiation workers. Under this limit the yearly maximum would be 1.2 r.

ing solar activity. The hazard due to the cosmic rays has already been estimated in preceding paragraphs; that due to the lower-energy particles cannot be evaluated until appropriate measurements have been made.

The hazard due to the solar proton beams can be a very serious one. By extrapolating balloon data to the top of the atmosphere, radiation levels as high as $3 \times 10^4$ roentgens (r) per hour have been inferred for free space.

## Shielding Considerations

The protons in the inner Van Allen belt and in the solar cosmic radiations determine the weight and type of material required to shield a spacecraft. The incident electrons are easily stopped in the material required to shield against the protons; therefore, the major hazard from these electrons is the x-rays produced as they stop in the shield.

In order to reduce the radiation level inside a spacecraft to a tolerable level, while the spacecraft is traveling through the radiation belt or is immersed in a beam of solar protons, it is necessary to surround it with sufficient material to stop all protons below a certain energy. The choice of material depends upon whether space or weight is critical, the energy of the protons which must be stopped, and the size of the cavity. Table 5 shows the thickness of material and the weight per unit area required to stop 200-Mev protons as a function of atomic number. Liquid hydrogen is the best material from the standpoint of weight; however, due to its low density the size of a shield becomes formidable. Carbon is the next best material from the standpoint of weight, and the thickness of the shield is satisfactory. If space, not weight, were the deciding factor, or if the thickness of the shield is comparable to the dimensions of the cavity to be shielded, a metal such as tungsten would be useful. Obviously, fuel, which is a hydrocarbon, batteries, and other structural materials will have to be strategically placed in a spacecraft to provide a portion of the necessary shielding.

The number of x-rays produced by an electron of a given energy is proportional to the square of the atomic number of the stopping material. After production the rate of absorption of these same x-rays is also proportional to the square of the atomic number of the stopping material. An ideal shield against electrons would consist of a layer of liquid hydrogen, to stop the electrons while producing a minimum number of quanta, surrounding a layer of material of high atomic number to absorb the photons that are produced. An excellent substitute for such an ideal shield can be made by placing a thin (0.25 cm) layer of lead inside the carbon shield used to stop the protons, provided the range of the electrons is less than, or equal to, the thickness of the shield. The maximum energy of the electrons in the outer belt is of the order of 1 Mev. The range of a 1-Mev electron is 0.42 gram, which is a small fraction of the 5 g/cm$^2$ shield thickness required to stop the protons.

Keller and Schaeffer (*3*) have calculated the total integrated dose which a man would receive inside a spacecraft, shielded with 0.25 cm of lead surrounded by a 2 cm (5 g) thick layer of carbon, which followed the same trajectories as Pioneer III and Pioneer IV. The values are 0.6 and 12 r, respectively.

## Implications for Space Missions

We have discussed the nature of the radiation and the properties of the natural phenomenon; now we will discuss the effect on space missions.

Of the three possible hazards—cosmic radiation, solar cosmic radiation, and trapped radiation—none will affect Project Mercury. The dosage from cosmic rays is reduced to 0.7 r per year due to the shielding effect of the magnetic field of the earth. This dosage is

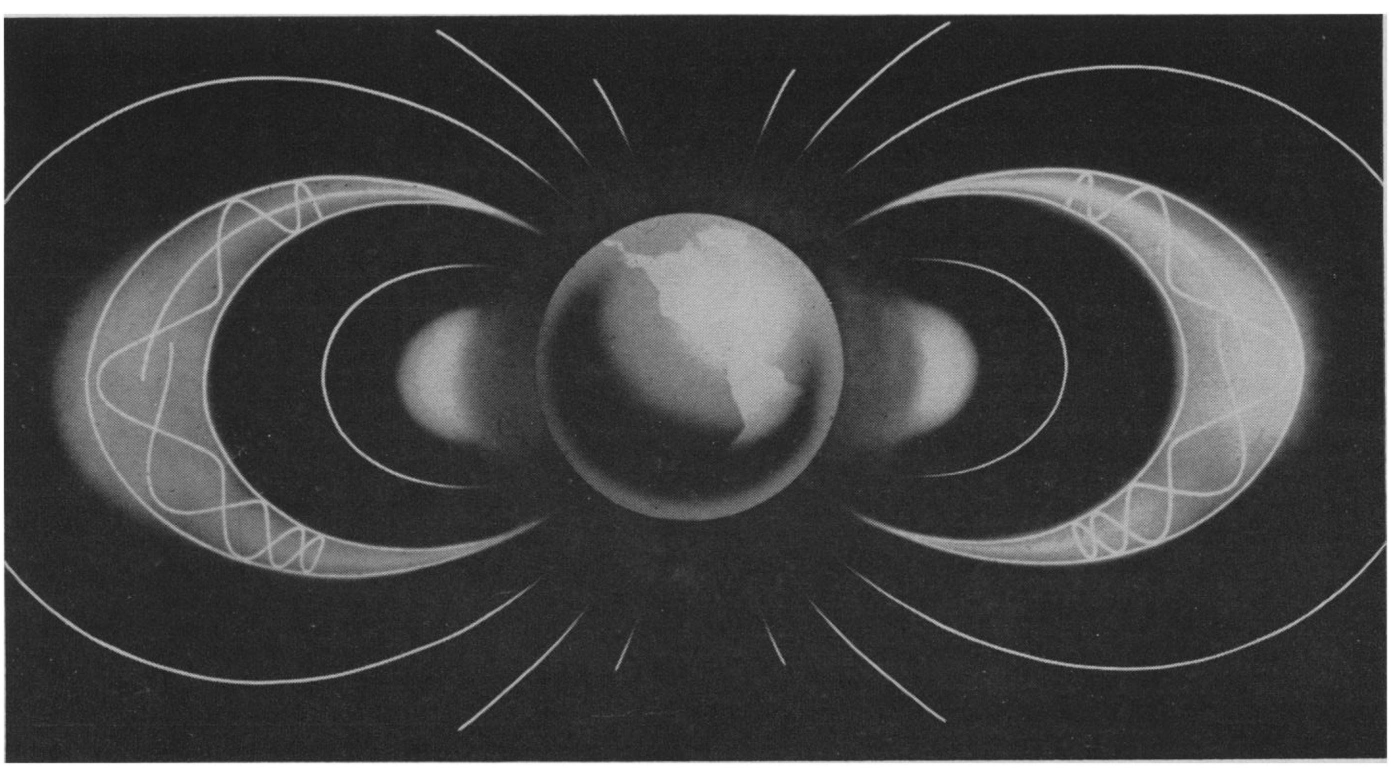

Fig. 4. Great radiation belts.

well within the prescribed tolerance. The slow, heavy nuclei have also been removed by the magnetic field. The actual number of particles which will strike an astronaut will be less than 5 percent of that which struck Colonel Simons during Project Manhigh. The orbit of Mercury lies below the inner belt; therefore, there is no danger from trapped radiation. The frequency of solar proton events will be down as the current solar activity declines. In addition, the magnetic field confines the protons from these events to the polar regions.

The trapped radiation and the solar cosmic rays are a hazard to those missions whose trajectories exceed an altitude of 500 kilometers or extend more than 60° north or south of the magnetic equator.

The radiation level inside the inner radiation belt exceeds 20 r/hr. The energy spectrum is flat; therefore, a large amount of shielding is required to protect a man in this region. It would require 45,000 pounds of shielding to reduce the radiation level to 0.5 r/hr inside a compartment 4 feet in radius. In 10 hours a man would receive his allowable yearly dose even with this amount of shielding. This would seem clearly to preclude manned observatories in this region.

The radiation level in the outer belt is high because of the bremsstrahlung produced by the electrons stopping in the outer shell of the spacecraft. The dose rate behind a 60-g/cm$^2$ carbon shield, due to the electrons in the outer belt, is about 1 r/hr. The addition of an inner layer of 0.25 cm of lead will reduce this dosage by a factor of 10. These figures are for the maximum in the outer belt and at a time of maximum intensity. However, again we can see that it is not possible to have manned vehicles in this region for extended periods of time.

In the region outside the radiation belts, the normal dosage will be the cosmic ray background level of about 5 to 10 r/yr. However, because of the solar cosmic rays, the solar proton beams, the shielding problem is complex. The outbursts of solar cosmic rays occur at random. At present, it is not possible to predict with certainty when such an event will occur; it is, however, possible by observations of solar activity to state that there is a high or low probability of an event within 4 or 5 days of the time of the observation. K. Anderson has worked up a method of prediction, based on the size of the penumbra of sunspots, that promises to be effective. Checks against past events are very encouraging (*4*).

Table 5. Shielding thickness for 200-Mev protons (thickness and weight per unit area, as a function of atomic number, for a shield which will just stop 200-Mev protons).

| Material | Atomic number | Thickness (cm) | Wt. per unit area (g/cm$^2$) |
|---|---|---|---|
| Liquid hydrogen | 1 | 176 | 12.3 |
| Carbon | 6 | 12.9 | 29.0 |
| Aluminum | 13 | 12.1 | 32.7 |
| Copper | 29 | 4.4 | 39.0 |
| Tungsten | 74 | 2.7 | 52.0 |
| Lead | 82 | 4.6 | 52.0 |

The magnitude of the exposure varies from event to event and cannot be predicted as yet. Our knowledge of the phenomenon is limited by the recency of its discovery. Furthermore, the amount of additional data which can be obtained is limited to the next year. After next year, there will be almost no opportunities to obtain more experimental data until 1967. By 1967, plans and vehicle construction for the circumlunar mission will be well under way. Therefore, the shielding concept for this mission must be solved on the basis of the data presently available. There are a number of factors to be considered: Should the vehicle carry sufficient shielding to keep the radiation level in the spacecraft below 0.300 r per quarter (the maximum dosage for radiation workers) for the largest flux observed to date? This will require an immense amount of shielding and may, by displacing redundant control systems that would otherwise be built into the craft, subject the crew to additional hazards of a different nature. Perhaps only sufficient shielding should be provided to protect the man during passage through the radiation belts; and the solar proton events should be regarded as an emergency. A small shielded "storm cellar" would be provided with sufficient shielding to reduce the radiation level to a level such that the man would not receive more than the 25 r emergency dose. Interplanetary flights would then be scheduled when the probability of a solar flare is small, just as airline flights are routed around tornadoes.

## Effects of the Radiation Environment on Materials

So far we have discussed the effect of the radiation on manned missions; before closing we would like to discuss the effects on materials. Generally, radiation dosages of $10^5$ to $10^6$ r are required to damage electronic components, and these dosages are not attained either from trapped radiation or solar cosmic rays. Therefore, as expected and observed, most electronic components will survive the radiation environment. However, an integrated flux of $10^{13}$ to $10^{15}$ 1.7-Mev electrons or $10^{10}$ 18-Mev protons on a square centimeter of solar cell will reduce the output to 75 percent of its initial value. Electrons of energy greater than 0.15 Mev and protons of greater than 0.2 Mev can cause damage to solar cells. Continuous exposure of bare solar cells in the center of the inner Van Allen belt could limit their life to a time which ranges from 6 hours to 5 weeks, depending upon

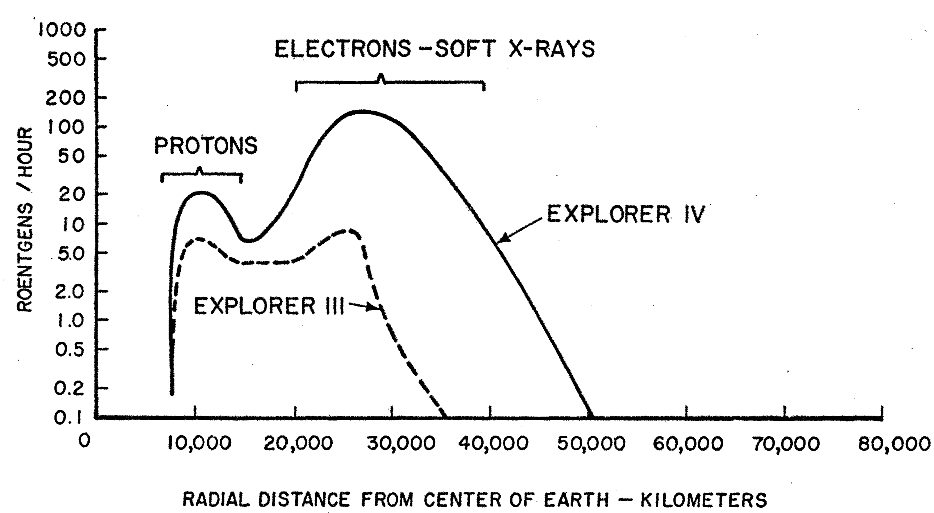


Fig. 5. Variation of radiation level along the trajectory of Explorer III and Explorer IV (*10*).

the proton flux which is assumed in the as yet unmeasured energy region below 40 Mev. The solar cells in Vanguard I are covered with a layer of glass and are still operating after 2 years of exposure to the inner belt. However, Vanguard I requires only a low-current drain, so that the full extent of damage may not be indicated in this case. In any event, this is not a very satisfactory method of eliminating the problem. Such a shield adds greatly to the weight of a solar power supply. Moreover, recent measurements by Denny (*5*) have shown that $10^{10}$ protons, of 350 to 750 Mev, per square centimeter, will also lower the efficiency of solar cells by 25 percent. Against such particles glass shields of reasonable thickness would be ineffective. Clearly, research and development are required to produce long-lived solar power supplies for use on satellites that must operate for long periods within the inner radiation belt. On the observational side, further measurements must be made in the 0.5- to 10-Mev region of the proton spectrum in the Van Allen belts to determine the exact shielding required.


**References**

1. S. C. Freden and R. S. White, *Phys. Rev. Letters* 3, 9 (1959).
2. E. P. Ney, J. R. Winckler, P. S. Freier, *ibid.* 3, 183 (1959).
3. J. W. Keller and N. M. Schaeffer, "Shielding of manned vehicles from space radiation," paper given at Aerospace Medical Association meeting, 9–11 May 1960.
4. K. Anderson, private communication.
5. J. M. Denny, "Radiation damage in satellite solar cell power systems," paper presented before the American Rocket Society Space Power Systems Conf., Santa Monica, Calif., 27–30 Sept. 1960 (*ARS Rept. No. 1295-60*).
6. C. L. Critchfield, E. P. Ney, S. Oleksa, *Phys. Rev.* 85, 461 (1952).
7. F. B. McDonald, *ibid.* 116, 462 (1959).
8. C. Fichtel, dissertation.
9. J. A. Van Allen, *J. Geophys. Research* 64, 1683 (1959).
10. ——— and L. A. Frank, *Nature* 184, 219 (1959).


# Science in the News

## John Kennedy's New Frontier: "The Margin Was Narrow but the Responsibility Is Clear"

The president-elect will take office with a mandate granted him by 50.2 percent of the major party voters and a Democratic majority of about 80 seats in the House of Representatives. Roosevelt in 1932 had 59 percent of the major party vote and a margin of 191 seats in the House. Kennedy has other disadvantages: he would not have won the election without the support of the conservative South; the country does not face as obvious a crisis as it did when FDR took office at the bottom of the depression; and before the nominating convention and to some extent today it is the more conservative Johnson rather than Kennedy who is the favored candidate of most Democrats in Congress. This, combined with the suspicion, or hope, depending on the politics of the observer, that Kennedy is really fairly conservative at heart has led to a good deal of speculation that the likelihood that the Kennedy administration will make a mark in history as a second New Deal can now be dismissed.

In the field of education, this means Kennedy would not succeed in putting through a massive program of federal support for public and higher education, for improving the economic position of teachers at all levels, and for removing the financial and social barriers that prevent or discourage students from poor families from going on to college and graduate school. In science, it suggests that there will be no abrupt increase in the current rate of growth of federal support for research.

Those who take the view that Kennedy's New Frontier can now be dismissed as campaign talk see his administration following a line close to that associated with Nixon: more active Presidential leadership; a faster increase in the size of the federal budget than under Eisenhower, but still increases that could be called moderate; and an effort to revitalize the government with newer and younger men. They expect a progressive administration, but not one that could be called radical by anyone to the left of Senator Goldwater.

Among those who disagree with this evaluation is Kennedy, who told reporters in his first press conference after the election: "I went to the country with very clear views as to what the United States ought to do in the sixties. . . . I am going to do my best. . . . The margin was narrow but the responsibility is clear." And in a speech last January, the tone of which has been repeated frequently since, Kennedy told the National Press Club that the Presidency requires strong leadership by a man who is willing to risk incurring "the momentary displeasure" of the public he is serving. Kennedy, in turn, is supported by Harry Truman who, in a syndicated article published this week, pointed out that both Lincoln and Wilson were elected by a minority of the popular vote, a fact which discouraged neither from the strongest sort of Presidential leadership.

### Congress

Part, but only part, of the difficulty the new administration will face is that some of the ideas Kennedy and his advisers have talked of will be opposed as being too radical in themselves: Kennedy will probably have little trouble getting almost anything he wants from the Senate; the test will come in the House, where there is strong opposition in principle to a program like the plan for federal aid to teacher salaries, with its implied threat of the passing of a good deal of the basic responsibility for the country's educational system from the local to the federal government; to health insurance for the aged under social security, with its threat of eventual expansion to provide federal health insurance for everybody; to the Kennedy proposal on minimum wages with its intent to broaden federal regulation of wages and hours from the present control over businesses "involved" in interstate commerce to businesses "affecting" interstate commerce—that is, to almost every business of any consequence.

The Senate passed two of these proposals during the last session, and the third, health insurance tied to social security, probably would have passed if