Title
RADIATION AND LIFE IN SPACE

Author
Tobias, Cornelius A.

Publication Date
1959-09-01

UCRL 8903

cy 2

University of California

Ernest O. Lawrence Radiation Laboratory

Berkeley, California

UCRL 8903
this replaces cy 2
(1960-69)

RADIATION AND LIFE IN SPACE

CORNELIUS A. TOBIAS

Donner Laboratory, University of California, Berkeley, California

WE CANNOT imagine life on this earth without radiation. Biosynthesis of some essential organic molecules proceeds by photosynthesis, thus making visible radiation essential to life. The more penetrating natural radiations from the radioactivity of the earth and from cosmic radiation have been present since the beginnings of the solar system and appear to have a definite role in causing genetic variation. Thus radiation is a factor in evolution. Studying the Universe, we must perceive at once that conditions on the surface of the earth are very special indeed to allow physical, chemical and radiation environment so gentle and stable that in the span of perhaps less than two billion years a great manifoldness of living organisms has arisen.

As far as man can reach with the tools of astronomy, the Universe consists of highly dense matter in the stars which are in a state of thermonuclear interaction at many millions of degrees temperature. The space between the stars is a very high vacuum except where filled by cosmic gas, dust or ionized plasma. The entire spectrum of known (and perhaps unknown) electromagnetic and corpuscular radiations is present in space. At present it is believed that most of matter and radiation is within the galaxies, and if this assumption is true, then we know that the energy content of the Universe is mainly contained in the mass of the stars and to a very small extent in the cosmic radiation.

We receive a good deal of radiation from the sun ; part of the solar spectrum, visible light, is quite essential to life being the main energy source of photosynthesis. The visible infrared and ultraviolet spectrum also contribute to the surface and air temperature and keep these in narrow range. The sun appears to be a sphere of 5800° kelvin surface temperature having a spectrum of emission of electromagnetic waves near the theoretical 'black body' emission. Most of the ultraviolet and x-ray components are absorbed in the upper atmosphere, and the visible and infrared rays deposit an average of 2 cal/min cm^2 on the earth's surface (1). Deviations from the ideal 'black body' spectrum due to the higher temperatures of the solar interior, and the violent solar surface phenomena, have been demonstrated in measurements from high altitude balloons and rockets (2), and a summary of present-day knowledge is presented in figure 1. The most striking deviations are the emission lines from hydrogen in the solar atmosphere, the strongest of which is the Lyman alpha line in the far ultraviolet and the x-ray emission, coming in part from highly ionized atoms in the solar corona. During solar flares x-rays up to several million volts in energy reach the upper atmosphere, and the x-ray intensity at some wave lengths can be as much as 100,000 times the black body radiation.

The ultraviolet rays of the sun are in part responsible for dissociation of air molecules and the appearance of radicals of O, N, H and their products (3) above 50 km altitude. Lower, in the stratosphere, ozone gas is present which in turn absorbs near ultraviolet radiations, thus protecting life below. On the surface of the moon and on planet Mars the ultraviolet radiation could seriously influence the existence of living cells. It is in the region below 3000 A° where nucleic acids and protein absorbs strongest and where lethal and sterilizing effects of ultraviolet are greatest (4). Thus we can postulate that on Mars or the Moon living cells would have to be resistant to ultraviolet rays, possess protective coating or live in places sheltered from the direct rays. On the other hand, the surfaces of Venus and Jupiter appear to be well shielded from ultraviolet rays by their atmospheres.

Space ships can be shielded from ultraviolet rays and low energy x-rays; the more penetrating components of primary cosmic rays and their secondaries present a health problem. Actually the surface of the earth is quite well shielded from the more penetrating components of intragalactic radiation. The atmosphere, which absorbs most of the cosmic rays and the earth's magnetic field, deflects away most of the charged particles impinging on the surface. It appears that less than 2% of the primary cosmic ray intensity in space reaches us at ground level. These protective features are present to varying degrees on the other planets.

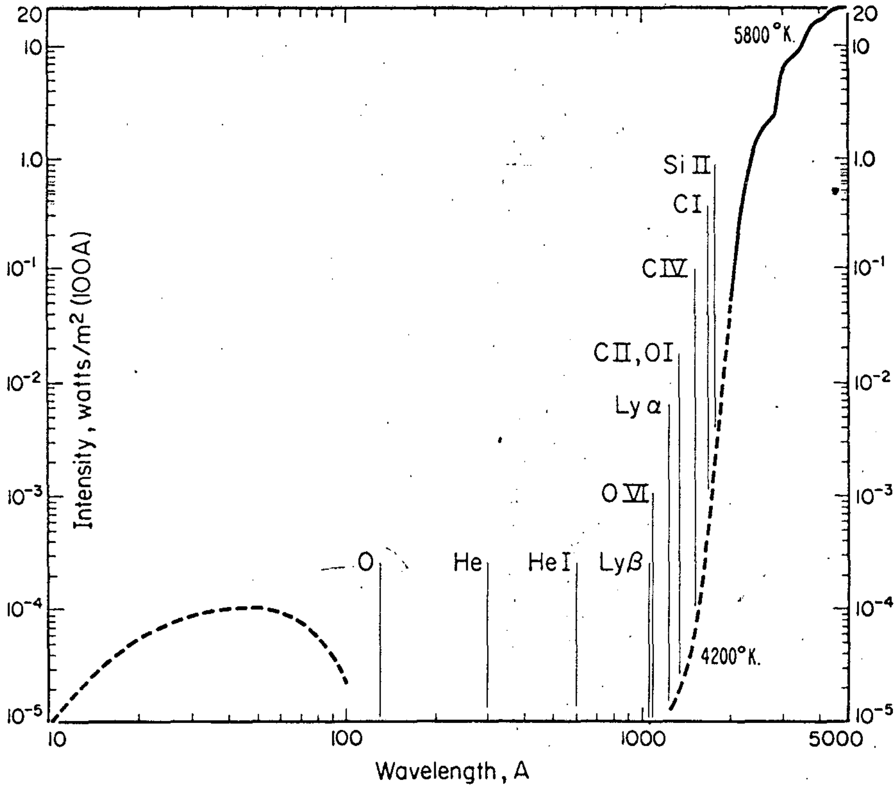

Fig. 1. Intensity of vertically incident solar radiation in spectral region below 5000 A°. In visible region sun appears to have surface temperature of about 5800 A°. This drops to about 4200 A° in the ultraviolet but several intense spectral lines of hydrogen and other elements have been observed in the far ultraviolet and soft x-ray region. X-ray region corresponds to a temperature of about 1,000,000°K and has great variations in intensity (2).

PRIMARY COSMIC RAYS

These are radiations which have their origin in extraterrestrial sources. Our present picture of the primary cosmic radiation is that of rapidly moving atomic nuclei, stripped of their electrons and converging incessantly on the earth homogenously from each direction in space (5). Protons are most abundant, and the frequency of heavier nuclei diminishes with increasing atomic number. In addition to the positively charged atomic nuclei electrons, fast neutrons, gamma rays and anti particles have been postulated as part of the primary rays, and we know that neutrinos are also present. Observation of the latter classes of primary particles has not as yet been successful because of their low abundance and the fact that such measurements need to be done away from the disturbing influence of the earth's atmosphere and magnetic field, at distances of more than 50,000 miles.

Near the earth a mixture of primary and secondary cosmic radiations is observed. Part of the primary flux of particles is reflected and another part captured by the earth's magnetic field thus causing a redistribution of particles. In the atmosphere by inelastic collisions the primary particles break up into a number of different kinds of secondaries.

Table 1 lists the frequency of various atomic nuclei in the primary cosmic radiation at rocket altitude. The heavy ion data were obtained by Yagoda (6) in high altitude rocket flights using photographic emulsions to record the tracks of the particles.

From the isotropic distribution of the primary rays, it seems clear that the majority of them must originate outside of the solar system, and in order to explain their presence one must propose a satisfactory injection and acceleration mechanism, as well as one for elimination of some

TABLE 1. FLUX AND DISTRIBUTION OF CHARGE AT 41° N. IN HEAVY PRIMARY COSMIC RAYS (6)

Nucleus	Abundance %
Carbon, nitrogen, oxygen	58
Fluorine, neon	9.1
Sodium to silicon	20
Silicon to calcium	low
Calcium and iron	11

Total heavy flux 4.98 ± 0.65 m^{-2} sec^{-1} sterad^{-1}

of the particles. We know several types of stellar events that involve emission of ionized matter into space. Fermi (7) suggested that collisions of particles with ionized magnetic clouds can cause their acceleration. From general considerations of energy density in space, it is now believed that most of the cosmic rays within our galaxy originate here and are contained within it (8) by virtue of the magnetic fields at the edge of the galaxy. The particles may have a mean life of perhaps 10^6 years before they escape into intergalactic space. The strongest sources of cosmic rays in our galaxy are believed to be the radio stars, many of which are located near the center of the galaxy (9).

The level of cosmic radiation is governed by the equilibrium between the generating process and the escape process and locally on the presence of magnetic activity resulting from cosmic clouds. The above outlined principles predict an energy distribution for the primaries in agreement with the experimentally found distribution at high energies per nucleon (above several Bev/nucleon). If $N(E)$ be the number of particles in energy range dE

$$\frac{dN}{dE} = -E^a \quad \text{where } a = -1.8$$

This relationship is followed up to the highest primary events: $E \sim 10^{16}$ ev.

RADIATION BELTS

With the first successful American satellite, Explorer I, regions of high intensity radiation around the equator were discovered, now bearing the name 'Van Allen radiation belts' after the leader of the research group which made the original observations (10).

Although much remains to be learned, we already have some detailed knowledge of the nature and origin of these rays, best summarized in Van Allen's own reports (11–14).

In Geiger Mueller counters up to 600 km the counting rate is low, and the radiation is chiefly due to the penetrating component of cosmic rays, being about 15 millirem per day. It is believed that one could send a manned satellite to this region without undue radiation risk to the crew (15).

Above 600 km the radiation intensity doubles for each 100 km altitude until the peak of the inner zone is reached at about 3400 km. From here the radiation intensity decreases again to an altitude of 8000 km, then goes through a second peak at about 18,000 km. At 17 earth radii the cosmic ray counting rate is down to about 2 per second. Actually some data are available up to 658,300 km (16) which is well beyond the moon.

The moon has no appreciable influence on the intensity, and according to Van Allen the omnidirectional cosmic ray intensity is 1.8 ± 0.3/cm^2 sec (March 3–6, 1959) whereas Vernov *et al.* report a value of 2.3 ± 0.1/cm^2 sec on January 2, 1959. Rossi earlier assumed that the energy flux of cosmic radiation in space is

$$3.5 \times 10^{-3} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$$

and that cosmic ray energy density in space is

$$1.4 \times 10^{-12} \text{ erg cm}^{-3} \sim 1 \text{ ev cm}^{-3}.$$

These figures correspond to about

$$7.2 \text{ primary particles cm}^{-2} \text{ sec}^{-1}$$

and to a dose level of about 25 millirad per day.[1] The measurements are about 3 times lower than the last figure. Knowing that variations take place in the intensity, more data seem necessary to know the average level.

Figure 2 presents our present idea of the distribution of radiation in the two radiation belts. There have not been enough rocket flights to know the exact distribution, but the actual distribution is at least as complex as the one shown.

Even before cosmic rays were discovered the existence of radiation ring currents around the earth was postulated by Poincare, Stoermer and others to account for minor variations in the earth's magnetic field. For some years both experimental (17) and theoretical evidence was available to the effect that a magnetic field can trap charged particles injected at the proper angle and energy. The particles, once trapped, spiral around the magnetic lines of force. The shape of the earth's magnetic field is such that some of the particles are reflected when they get

---

[1] 1 rad = 100 ergs g^{-1}; 24-hour day.

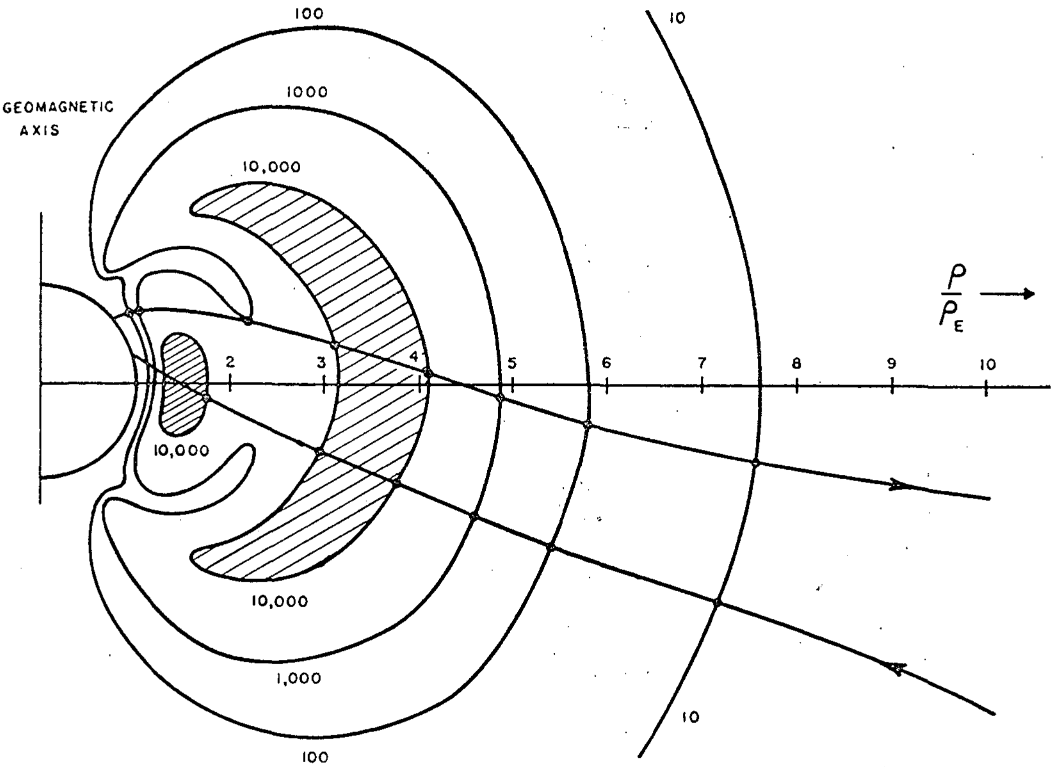

FIG. 2. A plot in a geomagnetic meridian plane of the intensity structure of radiation belts around the earth. Se is the earth's radius. Contour lines represent assumed extension of actual counting data which were obtained along the two lines indicated by arrows. Numbers associated with the several contours of constant intensity are the true counting rates in counts per sec. of a Geiger Mueller tube in Pioneer III or in satellite 1958E. From Allen (12).

near 40° latitude north or south. Moving in the earth's magnetic field it is possible that the particles will be accelerated also, due to gradients in the magnetic field.

The radiation intensity in the Van Allen band is high because particles are trapped in a finite region of space. It is believed that at least in the outer zones renewal of the electrons and some of the positive particles happens when the earth collides with an ionized magnetic cloud originating perhaps from the sun. The outer belt with its low magnetic field appears to be more efficient in retaining electrons than positive nucleons, and very few if any of the latter are present.

There is direct experimental proof based on tracks of particles on photographic emulsions (18) that the inner belt in addition to electrons contains protons up to 700 Mev kinetic energy. According to suggestions and theories by Christofilos (19), Singer (20) and others, these protons are the result of radioactive decay of neutrons which are produced by inelastic collisions of primary cosmic rays in the upper atmosphere. The neutrons decay into protons, electrons and neutrinos with a twelve minute half-life.

Loss of particles from both radiation belts can happen along the magnetic lines of force near the north and south poles, particularly during magnetic storms. It is believed that the particles thus lost from the radiation belt are at least in part responsible for the auroral phenomena.

The storing capacity of the radiation belt for charged particles has been directly demonstrated in the 'Argus' experiments originated by Christofilos (21) when small atom bombs were exploded between the two natural radiation belts. As observed in satellites and rockets (22), artificial radiation bands resulted. By such means it is possible to cause regions around the earth with considerable radiation intensities and persistence—a potential man-made hazard to space travel.

Particles are lost from the lower radiation belt also by scattering with the atoms of the earth's

TABLE 2. VAN ALLEN RADIATION BELTS (AUGUST, 1959)*

Inner Zone

Altitude 3600 km above surface

	Energy	Intensity
Electrons	>20 Kev	2×10^9/cm^2 sec sterad
	>600 Kev	1×10^7/cm^2 sec sterad
Protons	>40 Mev	2×10^4/cm^2 sec

Outer Zone

	Energy	Intensity per cm^2 sec sterad
Electrons	>20 Kev	10^{11}
	>200 Kev	10^8
	>2.5 Mev	10^6
Protons	>60 Mev	10^2

* J. Van Allen and L. A. Frank.
Radiation measurements to 658,300 kilometers with Pioneer IV SUI 59-18, August 1959.

atmosphere. This phenomenon explains the low level of radiation below 600 km altitude where air pressure begins to rise.

Table 2 summarizes the present status of our knowledge with respect to intensity levels in the radiation belts (14). Without shielding the surface dose in the first 0.01 mm of skin would exceed 40,000 rad per second at the peak of the outer zone. Assuming a shield of 1 g/cm^2, of light material, the inner zone would give rise to about 10 rad/hour, the outer zone in the order of 50 rad/hour. Because of the presence of high energy protons in the inner zone, shielding there seems impractical. In the outer belt most of the electrons are stopped by 1 g/cm^2 absorber and further shielding is chiefly a matter of absorbing the secondary x-rays. Their half thickness in lead is about 0.7 g/cm^2 so that 4 g/cm^2 reduces the radiation to one rad per hour.

It would then appear that the radiation belts limit the desirable space, in which manned space flight should be encountered, to certain regions:

1) Flight below 600 km altitude seems reasonably safe.

2) A space rocket may safely leave the earth in a narrow cone near the magnetic poles.

3) Shielding of the order of 10 g/cm^2 thickness removes most of the hazard from the outer radiation belt.

4) Shielding of the protons of the inner radiation belt seems impractical.

5) Beyond about 15 earth radii the effect of the radiation belts may be crossed.

6) The radiation belts may be crossed by a rapidly moving rocket at the expense of receiving a few rem dose.

Many points remain to be explored. We do not know for example if particles heavier than protons are present. Some temporal variation in the belts has already been observed, but much more knowledge is needed. Dosage during magnetic storms at high latitudes should also be explored.

HEAVY PRIMARY COMPONENT AND ITS VARIATIONS

With increasing knowledge of the radiation belt attention is being focused again on the primary heavy particles. These particles have greater biological importance than their low relative abundance would indicate. They are important because their linear energy transfer (LET) or ionization density is much greater than that of protons or alpha rays (23). A heavy nucleon of charge Z will have LET Z^2 times greater than a proton moving with the same velocity. For example, an iron nucleus ($Z = 26$) when completely stripped of electrons has linear energy transfer 676 times a comparable proton. Heavy primaries which represent only about 1% of the positive primary flux actually contribute between ½ and ⅓ of the total dose in unshielded situations. It is also necessary to know the 'Relative Biological Effectiveness' of the heavy ions.

Our knowledge of the low energy end of the primary heavy nucleon spectrum has been very limited. Due to the geomagnetic cutoff only nucleons higher than about 0.7 Bev per nucleon reach the top of the atmosphere in the temperate zones. Over the magnetic poles lower energy particles could come in, and their absence led to an early conclusion to the effect that primary rays usually would not include many particles of low energy. Study of the cosmic ray variations has, however, shown that there are many low energy particles generated by the sun. Such particles arrive with preference in the northern temperate zones. In order to completely assess the possible radiation hazard we must know the charge spectrum and energy distribution of heavy primaries to levels lower than 100 Mev per nucleon.

COSMIC RAY VARIATIONS

A number of important solar flares have been recorded during the past 15 years (24). During an important solar flare in 1956 (25) there was an increase of as much as 30-fold in neutron intensity near ground level (26) within 15 minutes, reflecting similar increases in the primary particles (at 54°N, 71°W) whereas mesons only increased 58% (27). The increase in the primary low energy component, up to 4 Bev/nucleon, was much greater than that in the high energy part of the spectrum. One of the most interesting aspects of cosmic ray increases after solar flares is that the rays strike the earth in very uneven distribution. Firor calculated the probable zones of impact of cosmic rays on the earth's magnetic field; some zones receive more dose than others. Geomagnetic latitudes between 25° and 60° exhibit an increase, while the equatorial North American continent falls in the heaviest irradiated zone. Existing data on the geographical distribution of the flare-type increases bear out the theoretical predictions, and thus we are now quite certain that the particles arriving associated with the solar flares do originate in the sun and are accelerated in a reasonably direct manner. Extrapolation of available data led Schaefer (28) to the speculation that during solar flares the energy (E) distribution of heavy primaries might vary as E^{-6} or E^{-7}. If this were true, we could expect during flares 10,000 times the usual dose in a space ship with 1 g/cm^2 shielding. Taking into account the duration of the flare, a person might receive as much as 25 rad, and in unusually large flares possibly 10 times that amount.

During the International Geophysical Year about one flare a month has been reported. In order to know the flare radiation spectrum in detail it is necessary to send rockets and balloons to high altitude during various phases of each flare. Since we do not know of advance signs of an impending flare, constant optical observation of the sun is used. The first successful interception of a solar flare was in July, 1959. In this event it was reported (29) that the low energy component of primary cosmic radiation transiently increased by a very large factor. Measuring near the top of the atmosphere Brown (30) found for the energy interval 100 Mev $< E <$ 400 Mev that the number of protons increased like $E^{-4.5}$. It also seems reasonable that should one attempt to fly closer to the sun than we are at present, the cosmic rays of solar origin should increase in intensity at least as fast as the inverse square distance law would predict. Now a high primary radiation intensity in prolonged flight or in residence on one of the planets may make serious limitations on life span and evolutionary processes. Thus, solar cosmic rays should be considered in the definition and limitations of Strughold's Helioecosphere (31). Contributions of solar-flare doses of cosmic rays to the average dose level at ground level are not significant. The quantitative observations have been too recent, however, to predict what variation in the size of solar flares we may expect in times to come.

Flares are also accompanied by gamma rays probably secondary to nuclear interactions. Their energies of 3–5 Mev have been reported (30).

MAGNETIC STORMS

While high energy components of a flare can reach the earth in minutes or hours, most of the ion plasma expelled from the sun adds to the solar corona and some parts of it move in ionized 'magnetic' clouds which reach the earth in about a day. Collision of these clouds with the earth's magnetic field appears to cause a variety of events; one of these appears to be the discharge of low energy electrons and protons from the radiation belt near the polar zones with accompanying phenomena of aurora, redistribution of the Heavyside layers of electrons, radio blackout and world-wide meteorological changes. At the same time the magnetic clouds appear to act as effective shields for high energy galactic cosmic rays, so that at ground level the over-all cosmic ray intensity usually decreases for 1–3 days.

In addition to the solar flares, other types of solar events also influence cosmic ray intensity as reviewed by the author (32). Among these are variations with the 20-year solar cycle and a rather large variation with 11-year cycle corresponding to the frequency of sunspots.

THE BIOLOGICAL PROBLEM

If we are to insure radiation safety for man in rockets and satellites, there are important tasks remaining for the radiation physicist and biologist. Some of these will be listed briefly:

Dosimetry

In order to understand and measure the magnitude of biological hazard we must be able to measure the all essential factors. These include the measurement of the time rate of 'absorbed dose,' that is the energy transmitted to each unit mass of tissue per unit time. We should also know the nature, energy and spatial distribution of the radiations along with nuclear interactions they may cause in the atoms of tissue. The radiobiologist wishes to know the microscopic distribution of frequency of ionizing tracks with different ion density, that is the distribution of 'linear energy transfers.' Complete understanding of these factors requires development of special dosimeters. These should accompany biological test object on satellite flights. Their presence seems essential for some purposes in view of the very large spatial and temporal variations in cosmic rays.

Shielding

It may be stated that man or most living organisms could not exist for long periods of time in extraterrestrial space without some radiation shielding. We already know that a reasonable shield (1 g/cm^2) will stop a good deal of radiation, and with increasing knowledge refined shields can be designed, even though some parts of space (e.g. the inner radiation belt) still remain hazardous.

Biological Effects of Heavy Ions

We do have actual and potential means to study effects of heavy cosmic ray primaries on accelerated beams at ground level. The effects of proton and alpha particle beams have been under study for some 10 years using cyclotrons (33) and two linear accelerators which are available for study of heavy ion effects. At the Berkeley HILAC machine carbon, oxygen, neon and argon beams are available with 10 Mev energy per nucleon and a similar machine is available at Yale University. During the past two years the effects of these beams on some unicellular organisms (34), phage and enzymes have been studied, and a beginning was made toward studies on animal tissues, particularly skin and brain. The range of these particles is very limited, however, (500 microns in tissue for carbon) so that one should try to accelerate heavy nuclei up to levels of 1 Bev per nucleon in order to observe their effects on the whole animal.

When compared to effects of widely used radiations, heavy ions impress with their ability to inflict great local damage, distributed in a statistical manner to locations near heavy ion tracks. It is believed that the greatest effect of such tracks is on cells essential to the whole organism, e.g. certain essential parts of the central nervous system (hypothalamus, brain stem, optic nerve) or on cells of the developing embryo.

When the influence of radiation upon extraterrestrial life is being considered, many challenging problems appear. Can a single organism or a population adapt themselves to a high radiation level? The theoretical answer suggests that the highest level is the one where complete reproduction is possible for many generations before the dose received becomes lethal to the parent or, by genetic changes, to the offspring. For some lower organisms, for example yeast cells (35), we have some idea about the magnitude of these levels. For mammals our knowledge is mostly by inference.

When man visits other planets of the solar system he may be confronted with primordial conditions on some planets, strange forms of life on others, and perhaps he will find planets where ancient life has become extinct. It seems to be of import to ascertain the role of penetrating and solar electromagnetic radiation to the generation of biological materials and to the mutation and evolution of the species. Great strides are being made in these fields (36, 37), still we must admit that we do not know the relative role of radiation as compared to chemical environment and temperature in evolution. The interplay of these factors during the last two billion years of our own history has been of decisive influence in bringing the living systems to their present state.

The fundamental problems just mentioned can be vigorously attacked in our earthbound laboratories. No matter how far we can carry such investigations, it seems nevertheless certain that space travel will bring further surprises and much new knowledge.

REFERENCES

1. Kopal, Z. *Brit. J. App. Phys.* 7: 119, 1956.
2. Watanabe, K. *Advances in Geophysics.* New York: Acad. Press, 1958 p. 153.
3. Kaplan, J. *The Chemosphere.* Second Internat. Symp. on the Physics and Medicine of the Atmosphere and Space, November, 1958. New York: Wiley. In press.
4. Hollaender, A. (editor). *Radiation Biology, Vol.* ii, New York: McGraw-Hill, 1955.
5. Freier, Phyllis, E. J. Lofgren, E. P. Ney, F. Oppenheimer, H. L. Bradt and B. Peters. *Physiol. Rev.* 74: 213, 1948.
6. Yagoda, H. Geophysical Research Papers No. 60, ASTIA Document No. AD-152585, 1958.
7. Fermi, E. *Physiol. Rev.* 75: 1169, 1949.
8. DeHoffmann, F. and E. Teller. *Physiol. Rev.* 80: 692, 1951.
9. Unsold, A. *Zeitschrift für Astrophysik.* 26: 176, 1949.
10. Van Allen, J. A., G. H. Ludwig, E. C. Ray and C. E. McIlwain. *Jet Propulsion* 28: 588, 1958.
11. Van Allen, J. A., C. E. McIlwain and G. H. Ludwig. *J. Geophys. Research* 64: 271, 1959.
12. Van Allen, J. A. and L. A. Frank. *Nature, London* 183: 430, 1959.
13. Van Allen, J. A. and L. A. Frank. State

Univ. of Iowa Report SUI 59-18, August, 1959.

14. Van Allen, J. A. State Univ. of Iowa Report SUI 59-7, May, 1959.
15. Langham, W. H. Institute of Aeronautical Sciences Report No. 59-52.
16. Vernov, S. N., A. Y. Chudakov, P. V. Vakulov and Y. I. Logachev. Doklady Akad. Nauk SSSR 125: 304, 1959.
17. Chamberlain, J. W. *Advances in Geophysics.* New York: Acad. Press, 1958.
18. Freden, S. C. and S. White. Univ. of Calif. Lawrence Rad. Lab. Report UCRL 5581T, May, 1959.
19. Christofilos, N. C. State Univ. of Iowa Report SUI 59-16, 1959, p. 13.
20. Singer, S. F. *Phys. Rev. Letters* 1: 171, 1958.
21. Christofilos, N. C. Univ. of Calif. Lawrence Rad. Lab. Report UCRL 5548, 1959.
22. Van Allen, J. A., C. E. McIlwain and G. H. Ludwig. State Univ. of Iowa Report SUI 59-10, May, 1959.
23. Tobias, C. A. *J. Aviation Med.* 23: 345, 1952.
24. Elliott, H. In: J. G. Wilson's *Progress in Cosmic Ray Physics.* Amsterdam: North-Holland Publ. Co., 1952, Chap. VII.
25. Brode, R. B. and A. Goodwin, Jr. *Physiol. Rev.* 103: 377, 1956.
26. Lockwood, J. A., R. E. Yingst, A. R. Calawa and G. Sarmaniote. *Physiol. Rev.* 103: 247, 1954.
27. Firor, J. *Physiol. Rev.* 94: 1017, 1954.
28. Schaefer, Herman J. *Solar Influences on the Estra Atmospheric Radiation Field and their Radiobiological Implications.* Second Internat. Symp. on Physics and Medicine of the Atmosphere and Space, November, 1958. New York: Wiley. In press.
29. Ney E. P., J. R. Winckler and P. S. Frier. *Phys. Rev. Letters* 3: No. 4, Aug. 1959.
30. Brown, R. R. and D'Arcy. *Phys. Rev. Letters* 3: No. 8, Oct. 1959.
31. Strughold, H. *J. Aviation Med.* 26: 323, 1955.
32. Tobias, C. A. Univ. of Calif. Lawrence Rad. Lab. Report UCRL 8115, January, 1958.
33. Tobias, C. A. and T. Brustad. *Radiobiological Studies with Accelerated Heavy Ions.* Second Internat. Symp. on Physics and Medicine of the Atmosphere and Space, November, 1958. New York: Wiley. In press.
34. Born, J. L., *et al. Progress in Nuclear Energy, Series VII* 2: 184. New York: Pergamon, 1959.
35. Tobias, C. A., R. K. Mortimer, R. L. Gunther and G. P. Welch. *Proc. of the Second Geneva Atoms for Peace Conference,* Geneva: United Nations, 1958, vol. 22, p. 420.
36. Miller, S. L. and H. C. Urey. *Science* 130: 245, 1959.
37. Calvin, M. *Am. Scientist* 44: 248, 1956.