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FOREWORD

This report was prepared by the Research Department of the Research & Development Division of American Machine & Foundry Company in Alexandria, Virginia, under Contract No. AF 33(616)-7631. The contract was administered by the Biomedical Laboratory of the 6570th Aerospace Medical Research Laboratories, in support of project 7165, "Health Hazards of Materials and Radiation," task 716503, "Human Factors of Nuclear Operation." Research under this contract began October 1960 and was completed in November 1961; subsequently additional information was included to reflect changes in the state of the art concerning the trapped radiation zones available up to March 1962. Mr. Thomas J. McGuire and Mr. Jerry Speakman of the Physiology Branch, Biomedical Laboratory, monitored the contract and gave invaluable assistance in providing references, guidance and criticisms.

Valuable assistance was received from the following individuals who reviewed and commented on the work: Lt. J.T. Tinney and Lt. E. Parker of the Biophysics Division of Air Force Special Weapons Center, Kirtland Air Force Base, New Mexico; Maj. de Paul J. Corkhill of the 6571st Aeromedical Research Laboratory of Aerospace Medical Division, Holloman Air Force Base, New Mexico; Col. G.L. Hekhius, Col. Paul A. Campbell, and Lt. Col. Ralph Allen of the School of Aerospace Medicine, Aerospace Medical Division, at Brooks Air Force Base, Texas. Among the many other individuals who graciously forwarded reports of their efforts and suggested sources for additional information were Col. John E. Pickering, Dr. James A. Van Allen, H.J. Schaefer, Dr. Cornelius A. Tobias, Dr. Herman Yagoda, Dr. M.M. Shapiro and Dr. H. Friedman.

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ABSTRACT

The Space Radiation Guide is intended to be a reliable, easily understood handbook that will provide the reader with sufficient knowledge of the nature of space radiations to permit him to comprehend the total space radiation problem as it pertains to the hazards of manned space flight. The report is not intended to provide answers to all the problems, but, instead, to present much of the factual data currently known and to point out areas where information is sketchy and inconclusive. The radiations considered are cosmic rays, solar radiation, and the geomagnetically trapped (Van Allen) radiations. Included are chapters on instruments used for measuring these radiations, on shielding techniques, and on biological effects.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Jos M Quashnock

JOS. M. QUASHNOCK
Colonel, USAF, MC
Chief, Biomedical Laboratory

SPACE RADIATION GUIDE

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INTRODUCTION

GENERAL

The purpose of this report is to provide a guide for aerospace medical personnel responsible for devising protection against space radiation, for physical scientists just starting work in space radiation technology or working in allied space programs, and for advanced non-professional technicians working in these fields. This guide should aid these people toward a better understanding of space radiation environments. It should also serve to point out some of the biological effects of space radiation as well as to indicate some of the methods which can be employed to provide protection against the radiation hazard in manned space vehicles.

Greatest emphasis has been placed on describing the space radiation environments. Although the cosmic ray hazard is presently considered as one of the lesser deterrents to space travel, cosmic ray phenomena and environments have received the most comprehensive discussion in this report. The chief reason for this emphasis is that the phenomena and mechanisms affecting galactic cosmic rays are understood better than are those concerning solar proton emissions and geomagnetically trapped radiations. The more serious radiation hazards for space flight are the geomagnetically trapped (Van Allen) radiation fields and the solar corpuscular radiation associated with solar flares. On an interplanetary mission, the solar flare radiation hazard is of primary interest; but on an extended earth-orbiting mission at moderately high altitudes, the trapped radiation hazards are also of great concern.

The amount of knowledge concerning these latter radiation environments is remarkable considering the technical problems encountered in collecting the data. The rate at which new data has been collected has frequently exceeded the rate at which it could be analyzed so that certain ultimate determinations about these radiation environments are not well enough established to allow an adequate assessment of the associated hazards. Discussions of radiation environments in this report necessarily reflect this situation. In order to avoid further confusion in the literature, we thought it desirable not to add to the present proliferation of speculative material.

The portion of this report pertaining to biological effects is not intended to provide extensive details of damage by space radiations, but

rather is intended to provide the reader with some familiarity with problems as in determination of biological effects which may ensue. These effects can be controlled relatively easily in the laboratory and have been the subject of many intensive investigations since the start of the Manhattan District project about twenty years ago. Even so, many of the basic questions have not been answered. The biological effects of space radiation environments cannot be wholly defined until these environments can be simulated adequately in the laboratory or until many more biological experiments have been conducted in space. It is hoped that those most concerned will secure detailed information on biological effects from published treatises on the subject and that they will keep informed on new developments by reading appropriate current medical and space journals.

The portion of this report dealing with instrumentation for measuring the radiation environment inside and outside a space vehicle briefly describes some of the associated problems. General types of instruments and systems which can be used for the measurements are mentioned, but it is expected that those interested will obtain detailed information from readily available current technical journals and from government research reports.

Shielding is presently considered the most suitable technique for protecting personnel from harmful effects of space radiation. Solutions to shielding problems for some of the radiations appear to be rather straightforward. However, shielding from some radiations, in particular that from large solar flares, may impose weight requirements that are outside the capabilities of the thrust of proposed launching systems. Shielding calculation methods for space radiations are not drastically different from those for ordinary nuclear radiations. However, the calculations are only as valid as the assumptions made and the parameter data available. The discussion on shielding in this report points out some of the types of calculations that can be employed as well as some of the necessary parameters which need to be more firmly established in order to make the calculations more precise.

A section entitled "Explanation of Terms" explains the terminology used in this report.

SECTION II

SOLAR RADIATION

INTRODUCTION

Penetrating x-rays, ultra high energy solar cosmic rays, extensive corpuscular beams, gigantic flares, intense ultraviolet and infrared radiation, millions of degrees temperature: These are familiar phrases in both the popular and scientific literature of the times. They all refer to space radiation of solar origin. What do they mean? Unfortunately, a great deal of misunderstanding exists concerning solar radiation. It is the purpose of this chapter to review the various phenomena and discuss their importance from a biological standpoint.

The sun has been a subject for study by astronomers and physicists for many years; but with the advent of the feasibility of extraterrestrial travel, scientists and engineers from many other disciplines have developed keen interests in solar physics. For those concerned with the radiobiological implications of space radiation, study of the sun is an especially important subject. Though much is known about the sun and its effects, there are still many important areas which remain in the speculative category; this lack of knowledge is particularly apparent concerning the solar radiation environment and its effects on man beyond the protection of the earth's atmosphere.

Enough is known at present to establish, in a qualitative way at least, the biological hazards from solar radiation. In this presentation it is hoped that enough quantitative data is included to acquaint readers with the magnitude of the problems imposed by these radiations.

Those who may not have a familiarity with the sun will find that the following discourse serves as an introduction; while those who are versed in the subject may find it useful as an outline reference. From the standpoint of cosmology, our sun is a very ordinary and unimportant star; but due to its proximity, its influence on the earth and interplanetary space is dominant. With the exception of atomic energy and heat stored in the interior of the earth, all other sources of energy available to us have their origin in the sun. Energy transfer from the sun is, of course, our main interest here; and other aspects, such as internal physics and chemistry, are not discussed.

Solar energy is propagated into space by all three methods of heat transfer: radiation, convection, and conduction. The last of these, conduction, is insignificant, but in theory occurs through the tenuous

solar atmosphere and is mentioned for technical accuracy. Of the other two, electromagnetic radiation is responsible for almost all the energy transmission from the sun. However, the small fraction of energy carried by convection, i.e., corpuscular emanations, is vastly important to extraterrestrial flight because of its energetic quality in spite of its relatively low quantity. The effects of the two types of solar radiation, electromagnetic and corpuscular, are entirely different as one would expect from such different forms of energy. The diversity in substance and effect serves as a natural division in discussing these radiations. The solar electromagnetic spectrum, though it presents no insuperable biological hazards in the regions of interplanetary space of interest, should be considered as an environmental constituent because of its possible deleterious effects. But, mainly, a review of this spectrum should serve to dispel any fears that solar x-rays, ultraviolet, and infrared radiations are inevitably dangerous to man in space. Solar particulate radiations, on the other hand, may well pose the most serious impediment to safe ventures into interplanetary space. Knowledge of their characteristics and effects is of utmost importance.

THE SOURCE

Most of the sun's energy is thought to originate in the inner core. It is produced by the conversion of matter into energy--in this case the conversion is probably the transmutation of hydrogen into helium in a process called the proton-proton reaction. Each year the sun liberates 3×10^{33} calories of heat energy; this is about 1.5 calories for each gram of its mass. This rate of energy production will allow the sun about 100 billion years to convert its hydrogen into helium. The mechanism of this atomic furnace is well described in reference 1 and texts on astrophysics.

A brief outline of the sun's physical description is in order at this point. The solar mass is about 332,500 times that of the earth. Its diameter is 1,392,000 km (870,000 miles, or about 109 times that of the earth). Mean solar density is about 1.41 times that of water. Surface gravity is around 28 earth g. From the earth, the solar disk subtends an angle of about 1/2 degree, specifically 32'36" at perihelion and 31'32" at aphelion. The mean distance of the sun from the earth is about 149,500,000 km (98,000,000 miles; 8.32 light minutes). The sun's axial inclination to the ecliptic is 83°. Rotation varies with latitude--about 25 days for one revolution at the equator, 27½ days at ±45°, and 33 days at ±80°.

Present theories hold that the sun's interior consists of (1) a core in which the thermonuclear reactions take place, the energy being transported toward the exterior by radiative transfer; and (2) an envelope, perhaps 1/5 the radius, in which the energy rises toward the surface by

convection. Surrounding this interior is another gaseous envelope, the photosphere. This outer structure is a relatively thin layer which has an appearance of being the solar surface. Inspection of the photosphere under high magnification and resolution reveals that this visible "surface" consists of granules or cells on the order of 1000 km across which are thought to be regions of ascending currents, while the interstices between granules are probably regions of subsidence. The spectrum blended from all the layers of the photosphere indicates that the sun radiates as a black body of approximately 6000°K; however, as will be noted, this temperature is merely an indication of the overall pattern.

Extending for 10,000 to 15,000 km above the photosphere is a very inhomogeneous turbulent shell of gas called the chromosphere. At its base the temperature is nearly that of the upper photosphere, but in the lower chromosphere variations of adjacent regions result in temperature differences of thousands of degrees. Above the lower chromosphere, the temperature rises steadily to several hundred thousand degrees. Here, production of electromagnetic radiation is in the ultraviolet and x-ray regions and in radio frequencies rather than the visible part of the spectrum.

The structure of the chromosphere extends with no sudden demarcation into the sun's outer atmosphere, the corona. This atmosphere is completely ionized and extends outward into interplanetary space with greatly decreasing density. Even at the base of the corona, the electron density is not high in comparison to the terrestrial atmosphere: It is on the order of 10^9 electrons per cm^3 and falls to a density of perhaps 10^3 e/cm^3 at one astronomical unit. The foregoing densities apply only to within an order of magnitude. The corona is not at all uniform, exhibiting great irregularities in structure and in the phenomena associated with it. The temperature of this plasma is on the order of a million °K or higher. It is in this region that most of the solar x-rays are produced.

Optical examination of the corona can only be done at times of solar eclipse or with special cameras which artificially eclipse the sun's disk. The appearance is not symmetrical and usually exhibits great variations in the form of extensions and streamers. Figure 1 is a photograph of the corona. This light from the corona is not intrinsic but is photosphere optical radiation scattered by coronal electrons.

The foregoing description of the sun's structure does not include the features which collectively are known as solar activity. Many transitory phenomena occur on the surface of the sun and in its atmosphere, and these are most important from a radiobiological standpoint.

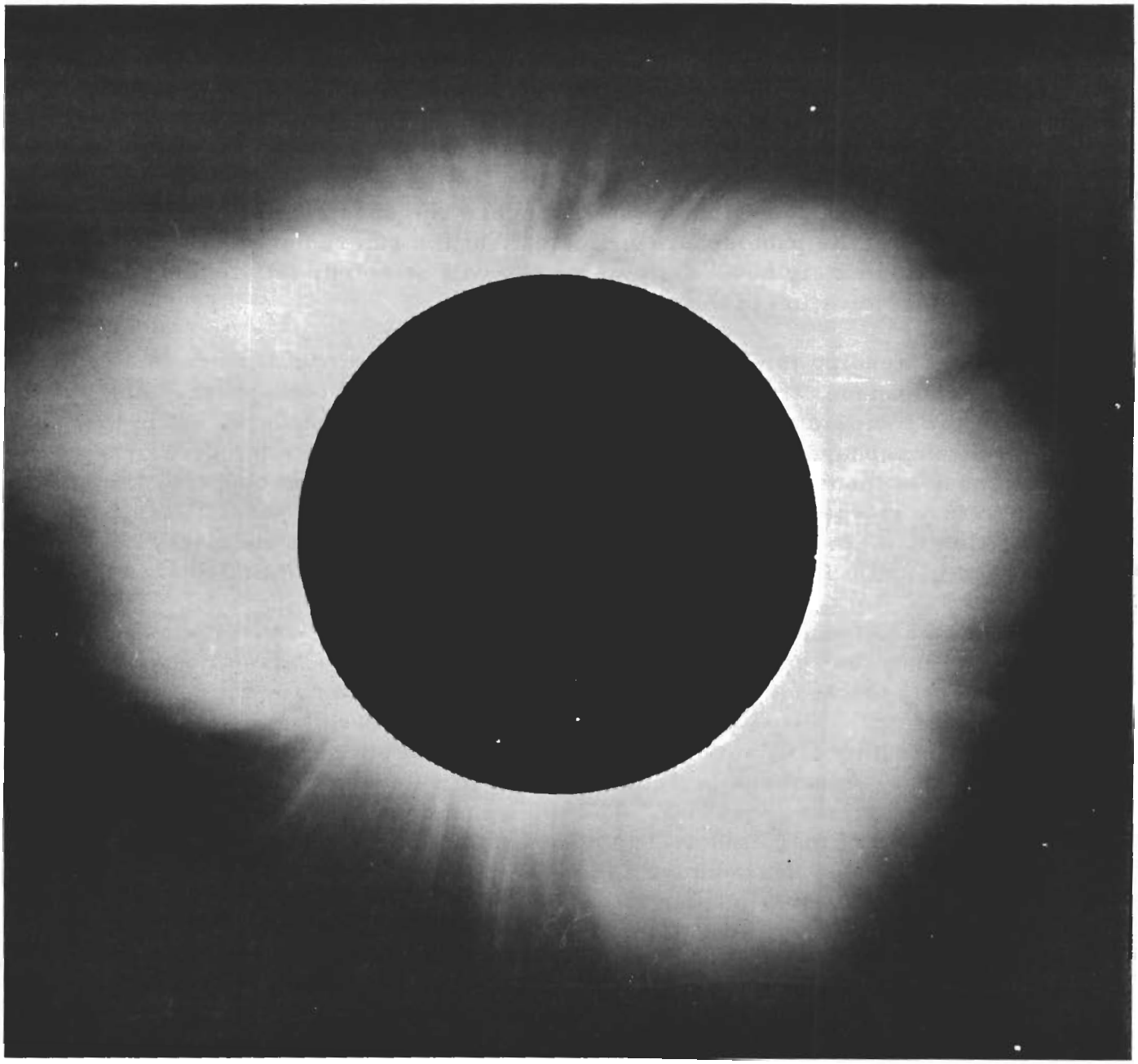


Figure 1. The solar corona during total eclipse. (Photograph from the Mount Wilson and Palomar Observatories.)

SUNSPOTS

Sunspots are perhaps the most commonly known features of the active sun, as the largest ones can be seen with the unaided eye when the sun's rays are filtered by haze or by artificial methods. Under magnification, spots appear to have considerable structure--the central regions, or umbra, are very dark, and are surrounded by filamentary areas known as penumbra, which are much brighter but still not as intense as the photosphere. The darkness of the umbral portions is actually an illusion due to contrast as these patches are quite hot. Estimates of temperature within sunspots are around 4000°K, about 2000°K less than the photosphere. Compared to the photosphere, equal areas of sunspots radiate about 10 percent as much total energy and even less in the visible spectrum. Spots occur in widely varying sizes from intragranular blemishes on the photosphere of about 1000 km across to giant regions as large as 100,000 km in diameter. They commonly are found in groups of widely varying size distribution. Lifetimes of individual spots are correlated to size and the largest sometimes persist for months. At the beginning of an eleven-year solar cycle, when the number of spots is at a minimum, they tend to occur at higher heliographic latitudes than they do at later times in the cycle. There is a definite tendency toward probability of occurrence closer and closer to the equator as the cycle progresses. Most spots fall between 5° and 30° latitude and rarely occur above 35° or below 5°.

The cyclic variation in sunspot numbers is very important to solar-terrestrial relationships as there are good correlations between such things as sunspot numbers and weather phenomena[1]. The effect on space radiation, however, is even more certain and more important. For it is in the regions of sunspots that solar flares emerge and these flares are the origin of the most significant radiation hazard in interplanetary space.

Let us establish what is mean by the term "sunspot number". It is not the exact number of individual spots as might be supposed, but rather it has been arbitrarily defined as

$$R = k\,(f + 10g),$$

where R is the sunspot number; g is the number of disturbed regions, whether groups or individual spots; f is the total number of individual spots; and k is a factor assigned to a particular observer and his telescope. Criticism of this index of solar activity has developed because of the disproportionate weight which individual disturbances, though small, give to the computed number, R. Nevertheless, the method does furnish

a representative picture of periodicity in solar activity, and interrelation with past records is a factor favoring retention of this system.

Figure 2 illustrates the regularity in the solar cycle over a period of 200 years[2]. Note that the magnitude of peaks varies by as much as a factor of three (cycles 3 and 5). Also, it should be pointed out that the cycles are not exactly eleven years, but average 11.2 years. Cycles have varied in length from as short as 7.5 years to as long as 16 years.

Associated with sunspots are other features of the active sun which deserve mention. Faculae or plages are extensive areas of brightness on the photosphere when monochromatic light is viewed, though they are sometimes visible in white light. On the average, they cover about 10 percent of the solar surface and always surround spots and spot groups, though they also appear in unspotted regions. Prominences are extremely variable projections of luminous gas thrust into the corona. The largest prominences reach truly spectacular size, sometimes on the order of 100,000 km in height in violent bursts of material traveling at velocities of hundreds of kilometers per second. Many prominences seem to be related to sunspots but they, like faculae, also appear on regions of the sun removed from spot activity. Filaments, once considered as other phenomena, are now recognized as being prominences viewed against the sun's disk rather than against sky background at the limb.

SOLAR FLARES

Of all the variations in solar activity, one phenomenon stands out for its certain correlation with geophysical effects and radiation hazard in space--the solar flare. For all their importance, flares are surprisingly unspectacular to the visual observer; in fact, they are usually undetectable in white light. But in certain monochromatic portions of the spectrum, notably 1215A, flares appear as a sudden intense brightening of an existing plage region. Within their brief lifetimes of approximately one to three hours, they unleash potentially catastrophic amounts of energy in the form of corpuscular and short wavelength radiations. High and low frequency radio emissions are also greatly enhanced, furnishing another means of detection of flares. The mechanism of flare production is not known, but they always occur near sunspots.

Particle emissions, essentially all protons, from large flares are the only real cause of immediate concern to space travelers because the short wavelength radiations (ultraviolet, x-rays, and gamma rays), though sometimes enormously increased in comparison to the normal background, are not intense enough to create an extremely serious biological hazard. Flares are classified as follows: Class 1 includes those whose

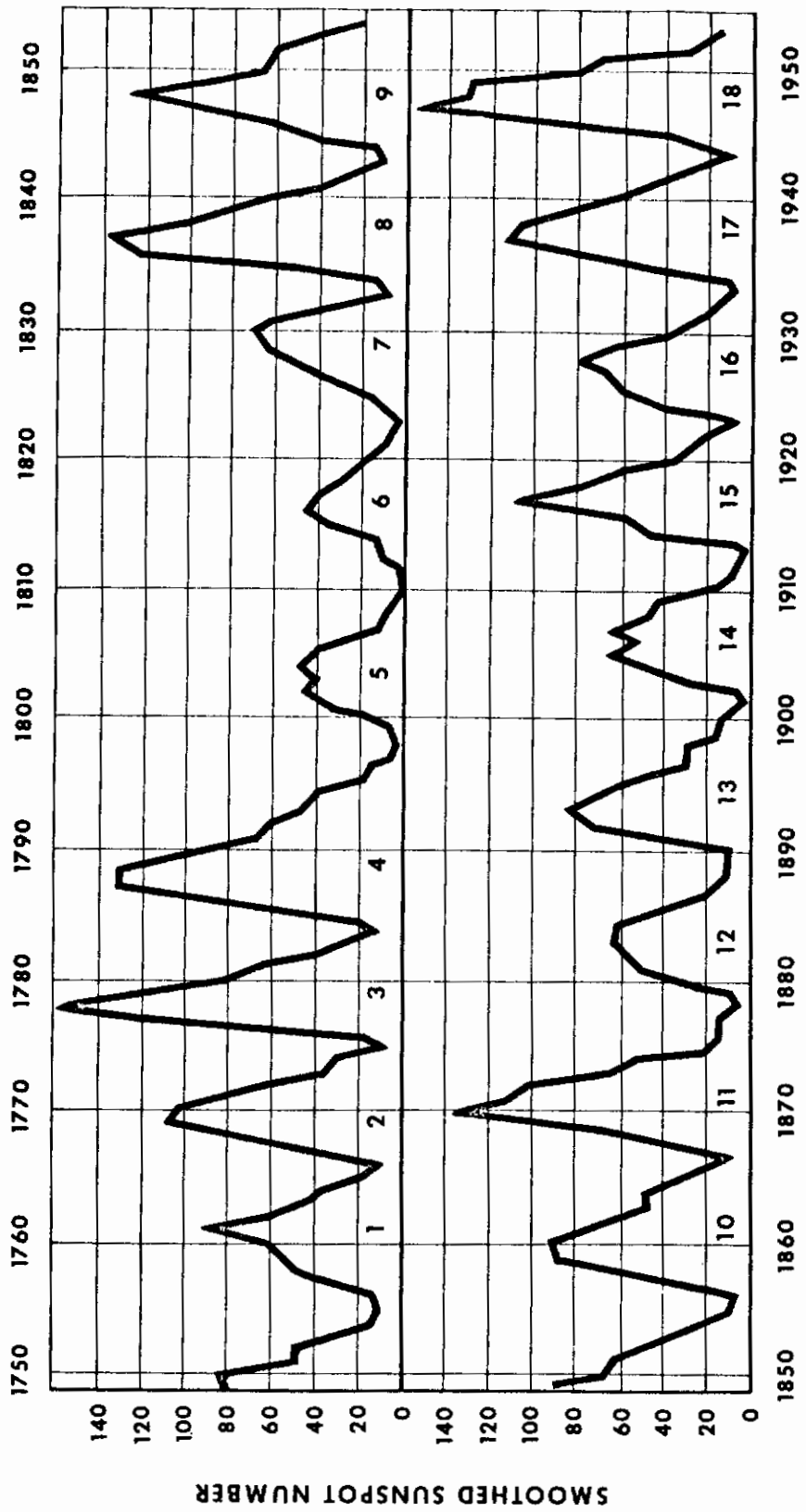


Figure 2. Solar cycles over a 200-year period. Note that the eleven-year periodicity is only approximate.

area is between 1×10^{-4} and 3×10^{-4} of the solar disk area; Class 2, those between 3×10^{-4} and 7×10^{-4}; Class 3, 7×10^{-4} or greater. In addition to the numerical classification according to area, a plus or minus sign may be added to indicate intensity. Major solar flares are those classified as 2+ or greater.

Figure 3 is a generalized illustration of the composite behavior of a number of large nonrelativistic flares[2]. "Nonrelativistic" means that there is an absence of particles whose velocity is near the speed of light. It should be noted that any particular flare does not always produce all of the geophysical effects shown in Figure 3, but that these effects are typical in the time scale indicated.

Frequency of occurrence in flares is closely associated with the sunspot number so that during the peak of the solar cycle flares are more numerous. During the last period of solar maximum important flares occured at an average of one per month. Those flares which produce particles of relativistic energies are less common; in fact, there have been too few to furnish much of a statistical basis for estimation of their frequency. They can be expected perhaps about once every four years[3]. The radiation environment and biological hazard attributable to these flare events is reviewed in the following discussions.

SOLAR ELECTROMAGNETIC RADIATION

Because there is no great peril to space crews from the solar electromagnetic continum, the subject does not require a detailed discussion in this guide. However, some precautions are necessary and enough information to assess this environmental constituent in interplanetary space is included.

Practically all of the radiant energy from the sun is emitted in the near ultraviolet, visible, and infrared portion of the electromagnetic spectrum. Energy emissions in the very short wavelength region (x-rays) and in the very long wavelength of the spectrum (radio waves) comprise only a minute portion of the total. The approximate energy distribution of solar irradiance by percentage of the total is given in Table I on page 13 for several wavelength intervals. A very complete table of spectral distribution is included in reference 4.

Figure 4 is a spectral energy curve for solar radiation outside the earth's atmosphere. The dashed line shows the energy output for a theoretical black body solar disk at 6000°K, which is often used for calculation. However, the black body radiant temperature is different for each wavelength and these variations should be taken into account for exact calculations. Examples of approximate temperatures at which the sun radiates at several wavelengths are given in Table II on page 13.

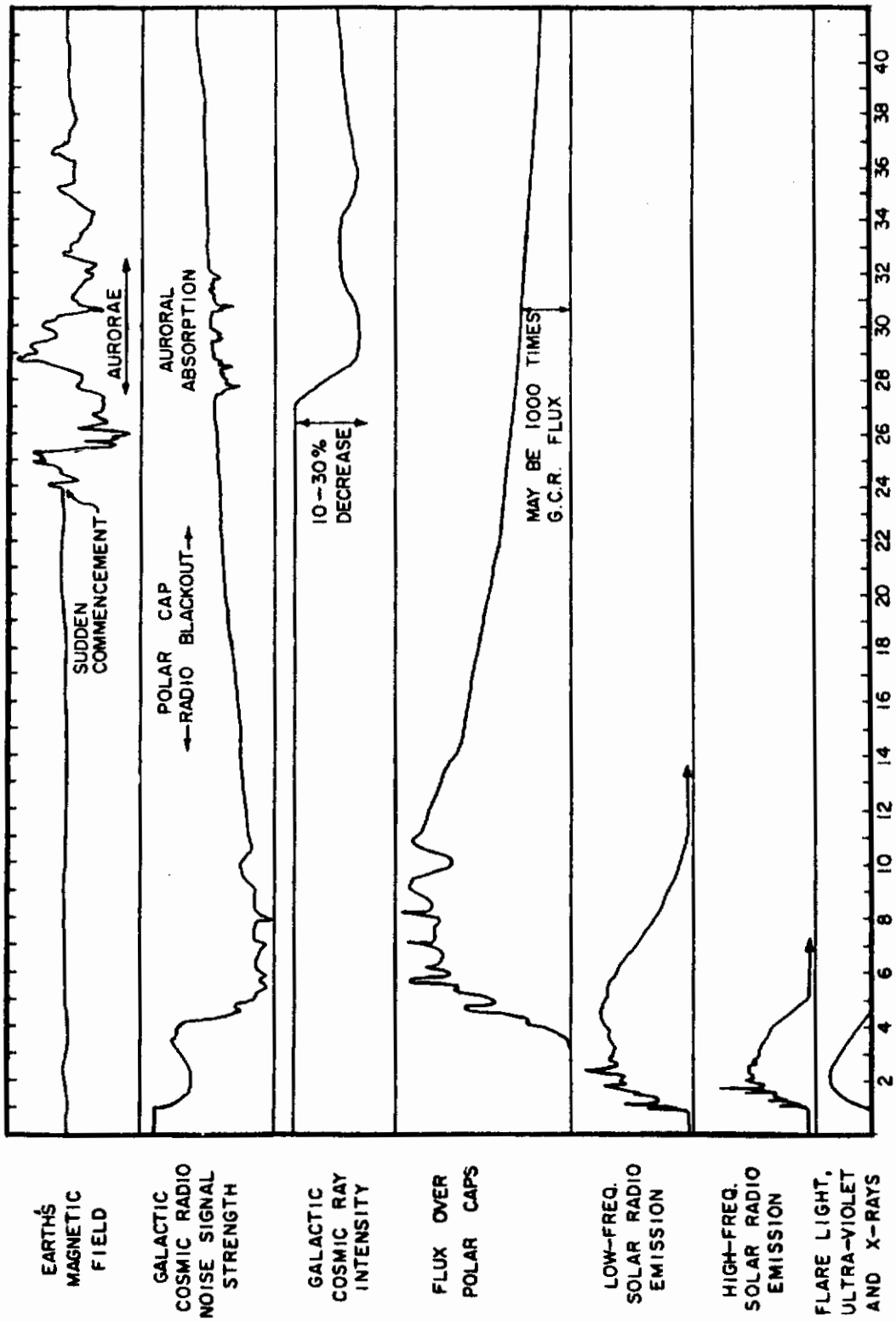


Figure 3. Typical time sequence of geophysical effects of large nonrelativistic solar flares.

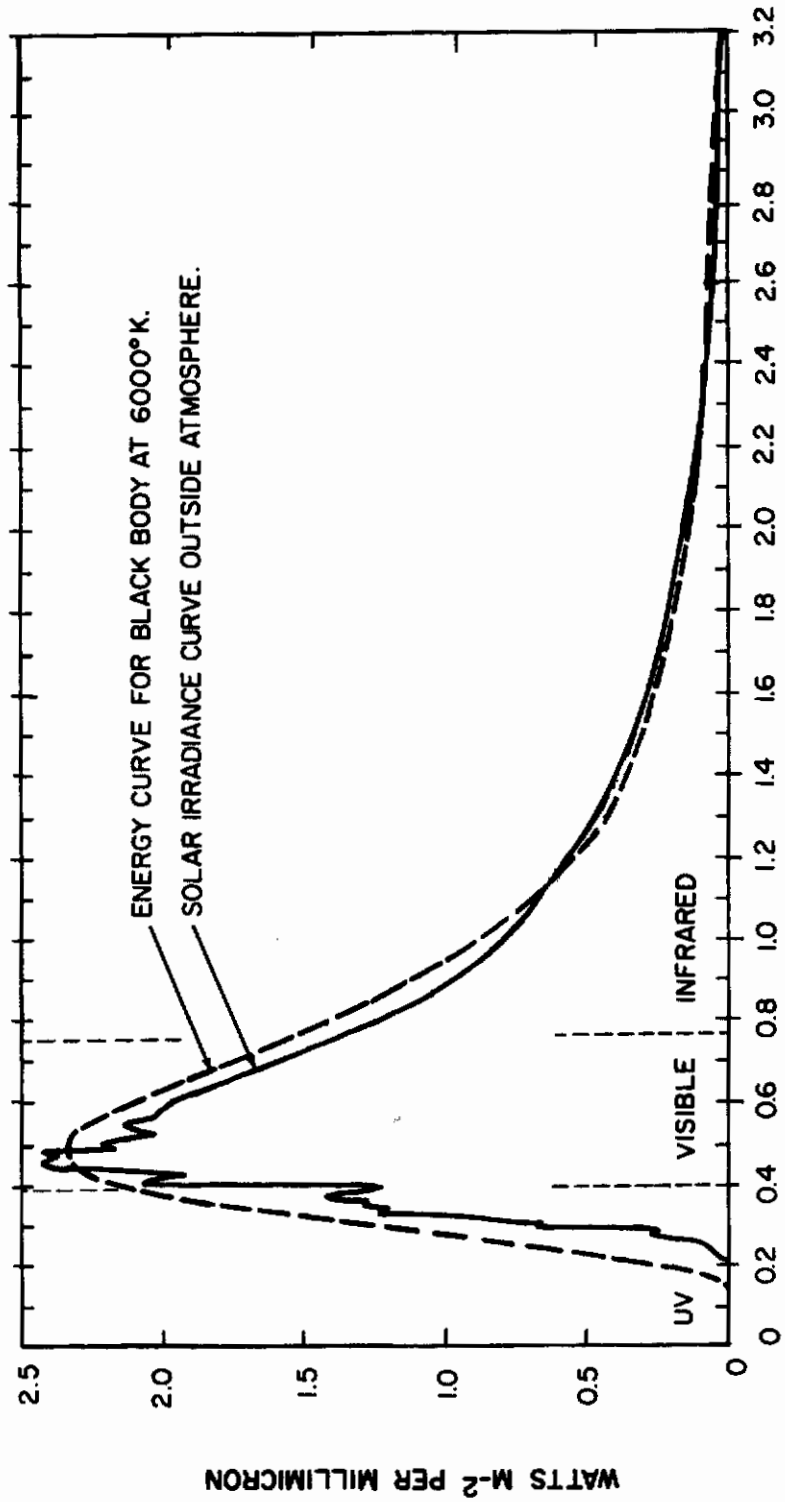


Figure 4. Spectral energy curve of solar radiation.

TABLE I

Energy Distribution of Solar Electromagnetic Radiation

Type	Wavelength Interval in Angstroms	Approximate Percentage of Radiant Energy
x-ray and ultraviolet	1 to 2,000	0.2
ultraviolet	2,000 to 3,800	7.8
visible	3,800 to 77,000	41
infrared	7,000 to 10,000	22
infrared	10,000 to 20,000	23
infrared	20,000 to 100,000	6

TABLE II

Solar Radiation Temperatures

Wavelength, A	Temperature, ^{o}K
3500	5500
2900	5500
2600	5000
2200	4900
2000	4500
1500	4500
1200	6000

The total energy output is remarkably constant--variations caused by sunspots and associated activity are less than 0.4 percent. This radiant output is called the solar constant and in terms of heat energy has a value of 2.0 cal/cm^2/min ±2% (7.37 Btu/ft^2/min) at the earth's orbital distance of one astronomical unit. Irradiance at other distances varies according to the inverse square law:

$$I = \frac{I \text{ at earth}}{R^2 \text{ in A. U.}} .$$

Figure 5 gives values of irradiance and intensity compared to earth at distances through the inner solar system.

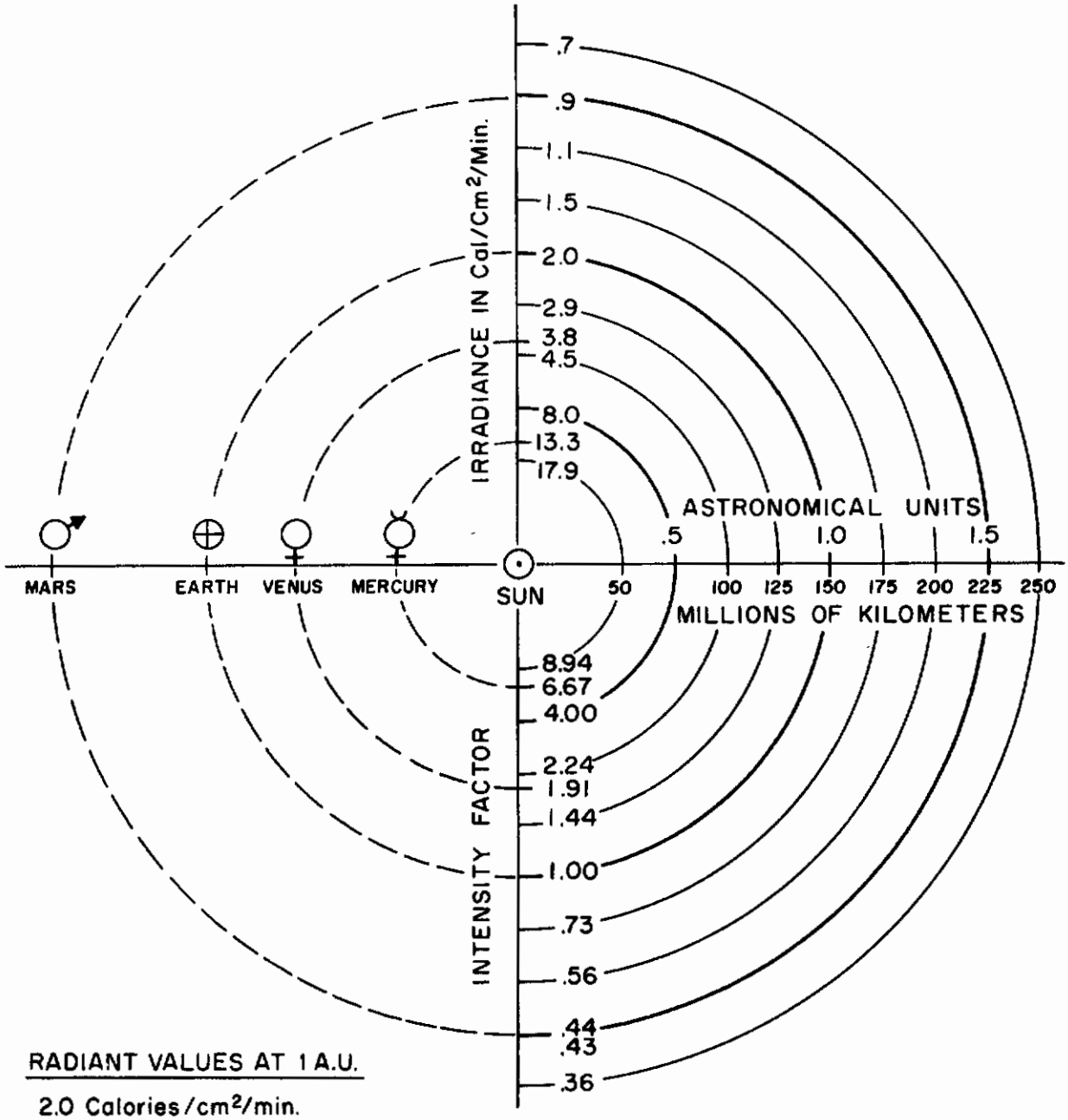
Beyond the influences of the earth's atmosphere, solar illuminance is constant at 141,400 lux (or 13,000 foot candles). For comparative purposes the highest value of solar illumination reached on earth under favorable conditions is about 100,000 lux. A rule-of-thumb comparison is that the sun's intensity in space is about 50 percent greater than at the earth's surface.

Though solar radiant energy is essentially constant, there are highly variable increases in the x-ray emissions during active periods. It must be emphasized that these transient bursts carry very little of the total energy because, though the wavelengths are short and energetic, the intensity is extremely low. Rocket observations of background and flare produced flux indicate that nearly all flares emit x-rays as hard as 20 kev; however, the extremely low intensity of such radiation is evident from the following table[5] of flux observed in a class 2+ flare.

TABLE III

Observed X-Ray Flux

Wave Energy	Wavelength Interval	Background Energy Flux	Class 2+ Flare Energy Flux
600 to 120 ev	20 to 100 A	0.6 erg/cm^2/sec	4.0 erg/cm^2/sec
1.5 kev to 600 ev	8 to 20	0.002	0.09
6 to 1.5 kev	2 to 8	0.00055	0.03
20 kev	0.6	---	0.000023



RADIANT VALUES AT 1 A.U.

2.0 Calories/cm²/min.
1.36 erg/cm²/sec.
.136 watt/cm²
92 ft. lb./ft.²/sec.
7.4 Btu/ft.²/min.
141,400 lux

Figure 5. Diagram of radiation intensity through the inner solar system. The intensity at any distance from the sun is equal to the radiant value at 1 A.U. times the intensity factor.

Since it is inconceivable that a person would be exposed in space without the protection of vehicle walls or a pressure suit, we may assume that space crews will never be without some material between them and the sun. This is a fortunate set of circumstances because, in terms of biological effect in space, the foregoing environment would be extremely severe were the rays not shielded.

Ultraviolet light on bare skin can cause severe burns, especially at high altitudes and in space if the skin were exposed. Another effect which could be serious without shielding is the tendency of ultraviolet below 3200 A to cause cancer of the skin[6]. Most types of glass and plastics offer adequate protection from ultraviolet wavelengths. Thicknesses of ordinary glass as small as 2 mm absorb ultraviolet below 3100 A. However, certain glasses and quartz do not furnish this absorption and protective devices should be incorporated if these materials should be used in windows or visors.

The visual spectrum of the sun does indeed pose a problem of eye protection, though probably not one of great difficulty. Since in space there is no atmosphere to scatter sunlight, the solar disk will not provide a warning glare as the line of sight approaches it. To the eye adapted to darkness in space, an inadvertant glance at the sun could cause a strong temporary disturbance to vision. It seems unlikely that one would look directly at the sun for more than an instant, but it should be noted that a gaze of ten seconds would be sufficient to cause a permanent retinal burn. The time of exposure for retinal burn is nearly the same at any distance from the sun, but the area of burn is inversely proportional to distance[7]. Protection of eyesight from sunlight, then, is a necessity and the problem of filtering intense glare without interfering with vision away from the sun must be considered.

Though solar x-rays during times of flare activity can cause enough ionization of the atmosphere to create observable geophysical effects, they are simply of too low intensity and of too low energy to penetrate spacecraft or suits to administer a significant dose to persons within.

SOLAR CORPUSCULAR RADIATION

From experiments with radiation detecting satellites and space probes, startling new problem areas in radiobiology have been discovered. One such new development is the hazardous characteristics of radiation trapped in the geomagnetic field. Another is the devastation potential of particulate (corpuscular) radiation produced in solar flares. While the Van Allen trapped radiation has received a great deal of attention, even in the

popular press, the danger associated with flare-produced particles has not received as much publicity and, in fact, is unappreciated by many otherwise well informed technical people. It is strange that this is so because the latter hazard is decidedly more dangerous and harder to cope with than the trapped particles.

Primarily, the particles of concern from the sun are protons. At present, there is very little data on the possible existence of heavier atomic nuclei in solar radiation but they surely comprise only a small fraction of the total number of particles. There is strong evidence that the sun emits corpuscles at all times--but whether or not this coronal expansion is a dynamic process or a nearly static one is open to debate[14]. Our interest here is in radiation, so let us consider the worst case, the dynamic one, to see what effect it would have.

Theoretical considerations based on observations of aurorae and accelerations of comet tails have led to a model of the "solar wind" which is a flow of ionized hydrogen gas (protons and electrons) from the corona having the following properties[8]:

Quiet Sun:	Density $10^2/cm^3$ at 1 A.U. Velocity 500 km/sec.
Active Sun:	Density $10^4/cm^3$ at 1 A.U. Velocity 1500 km/sec.

Even during active periods the kinetic energy of this plasma does not reach values high enough to cause concern for radiation damage behind small amounts of shielding. Protons with a velocity of 1500 km/sec have approximately 10 kev energy, a relatively small value.

Other estimates of solar wind properties have been given by various sources and it should be mentioned that literature searches[9, 10] report values given by theorists ranging in density from 10^{-1} to 10^5 particles per cm^3 and in velocity from 10^2 to 3×10^3 km/sec at varying solar conditions. Even at 3×10^3 km/sec, the proton energy is still only about 50 kev, not enough energy to administer a significant dose within shielding afforded by a space suit.

From the preceding it is apparent that the normal efflux of corpuscles from the sun need not be considered a hazard in radiobiology. It is during the extraordinary periods of flare eruptions that the radiation becomes significant to crew members in space, and we shall now take up

a discussion of flare events--the radiation environment produced as their result, their biological effect, and prediction aspects.

A note on definition is in order at this point. High energy solar corpuscular beams are frequently described as "solar cosmic rays", or simply "cosmic rays". Perhaps this is an ambiguous classification in view of the differences between these particles and in radiation of true cosmic origin. The table on page 19 outlines the principal variations in the two types of radiation.

From almost any standpoint, the two radiations can be distinguished and for the sake of clarity and consistency the term "cosmic rays" in this guide refers to the particle flux from beyond the solar system.

A complicating factor in determining the effects from flares is that they are inconsistent in their injection of high energy particles through the solar system. Sometimes the observable proton events are very minor in energy and intensity--these are usually attributable to the smaller flares, but not always. There are arguments for the existence of two distinct types of flare events instead of particle radiation of continually increasing energy and intensity with flare size. In the normal large flares which occur approximately once a month during high solar activity, the radiation does not include relativistic particles (those with velocity near that of light). But in the extraordinary flares such as the classic one which came on February 23, 1956, the onset of particles appeared almost at the time of the optical flare. So far there are no observations of flare radiation in the range of energy between that associated with the infrequent relativistic flares and that associated with the comparatively often occurring ordinary flares. Since there is this distinction, it would seem proper to separate the types in the following discussion. However, it should be noted that there is a possibility that nonrelativistic flares are only the low energy portion of a continuous distribution in which giant flares represent the high energy end[11]. Our concern is for the characteristics of the corpuscular outbursts--primarily their energy-intensity spectra, time variations, and propagation into space.

Nonrelativistic Flares

During the last four-year period of solar maximum, there were 30 flares of nonrelativistic character which produced radiation of serious proportions in terms of biological hazard. Behind moderate shielding (about 5 gm/cm^2) it has been estimated that six of these would have inflicted near-lethal doses, while the remainder would have produced doses of various amounts ranging down to only a small amount above the normal

TABLE VI

Distinctions Between Galactic Cosmic Rays and Flare-Produced High Energy Solar Particles

Criterion	Cosmic Rays	Solar Corpuscles
Spatial distribution	Isotropic beyond terrestrial influence (no preferred direction of arrival)	Nonisotropic at onset, later becoming diffused through solar system
Composition	Approximately 75-80% proton, 15-19% helium nuclei, remainder nuclei of heavier elements to atomic numbers 26 or 27	Almost all protons, some alpha particles, no evidence for heavy nuclei
Temporal variations	Permanent phenomenon, practically constant with time	Transient radiation, greatly variable with time
Energy	Extending to at least 10^{17} ev in some cases (much greater maximum than solar particles	About 10^{10} ev highest recorded
Origin	Theories only; perhaps supernovae explosions in the galaxy	Active regions of flares on the sun
Intensity	Relatively low: about 2 particles/cm^2/sec of all energies	Very high: may be as high as 10^8 particles/cm^2/sec
Biological effects	Primarily chronic; perhaps some vital cell destruction	Primarily acute damage; possible sudden illness; incapacitation, or death

galactic cosmic ray dose[12]. Because of the duration of each of these solar proton emissions, the particles were present in detectable intensity above atmospheric shielding for about 15 percent of the time during this period of high activity.

Typically in these proton events, the arrival of particles at the earth comes from about one to five hours after the optical flare is first detected. High and low frequency solar radio storms often accompany the arrival of solar corpuscles. A time sequence of geophysical effects associated with these flares is shown in Figure 3 (page 11) as an example of a typical flare disturbance. Note that the particle flux gradually decays over a period of many hours, sometimes not arriving at the pre-flare level for several days.

Decay in particle intensity usually follows a $1/t^2$ law, i.e., the number of particles/cm^2/sec is inversely proportional to the square of the time in hours after the first hour. In terms of radiation, this means that the dose rate is much higher in the initial stages; so high in fact that about half the entire dose can be expected within the first hour after radiation onset.

It is important that the events taking place in interplanetary space during this time be understood by those who must devise countermeasures for the radiation. Fortunately, the rather vague theories of a few years ago which attempted to explain these phenomena are now becoming reinforced by experimental evidence so that in a general sort of way the radiation behavior is known. The dependence of the corpuscular distribution on magnetic fields should be emphasized. Whenever charged particles cut across magnetic lines of force, they suffer deflections from their paths so that protons which originally are ejected radially from the sun may undergo changes in direction which completely alter their locations and direction of arrival in space. Those particles of lower energy are more susceptible to deflection while those of high energy, sometimes referred to as having high magnetic rigidity, are influenced less so that they tend to adhere to their original directions. When a corpuscular outburst occurs in a flare, a wide range of energy is represented by the particles. Those with the highest magnetic rigidity are detected at the earth first because not only are they moving faster but they have shorter path lengths due to relatively small deflections. Often the first particles arrive nonisotropically; that is, from a preferred direction in space. Later, as the deflected particles arrive there is a gradual shift toward isotropy, an observance in keeping with the theories of turbulent magnetic fields in space. At the geomagnetic equator the field lines of the earth strongly repel the radiation while at the poles the particles undergo concentration so that they are always detected first at high latitudes.

In interplanetary space, solar plasmas (positively and negatively charged high energy particles) influence the solar magnetic fields and the field lines of force in turn direct the particles with a resulting turbulence of particles and lines of force which serves as a particle storage mechanism. It is believed by many that the corpuscular outbursts are discharged into space in what are originally well-defined beams, or streams of particles. Then under the disturbing forces encountered as the protons cross magnetic lines they begin diffusing through regions of space far from the parent beam. This process is illustrated in Figure 6. Note that although the emission from an active region may terminate within hours, corpuscles, once they become involved in the storage fields, may permeate space in all directions for extended periods.

An interesting corollary to this model of fields and particle interaction is that flares on the western limb of the sun should propagate directly to an observer along the initially radial, but ultimately bent, magnetic lines extending from a flare. Those particles issuing from a mid-disk or eastern limb flare would not travel so directly and would arrive later after a diffusion process has taken place in the disordered fields. In Figure 7 a series of flare positions are plotted against the time delay between the optical flare and particle arrival, demonstrating that western limb flares may provide less warning of a sudden increase in radiation.

The first and most energetic particles to arrive at an observer in space would be those moving parallel to radial field lines and would appear to come from the sun's direction. Later, irregularities in the radial field would result in observations of isotropy for the remaining radiation. It should be recognized that morphology of protons and magnetic fields, as shown in Figure 6, is rather schematic at best; in fact, there is some evidence that solar corpuscular beams are projected over a 2π solid angle, that is, an entire hemisphere above the flare region[13].

As mentioned previously, flares and their associated proton events are always produced in areas of high sunspot activity. As the sun rotates about its axis the spot groups are carried across the disk as shown in the sequence of photographs in Figure 8. This is a particularly persistent group. As such a region of activity travels across, there may be a succession of particle acceleration events which are attributable to it. Once a spot region rotates to the back side of the sun, there is no further evidence of particles reaching the earth from it, though surely flares continue to arise. It seems safe to say that an absence of active regions on the visible face of the sun nearly always corresponds to an absence of high energy solar protons at an observer's location.

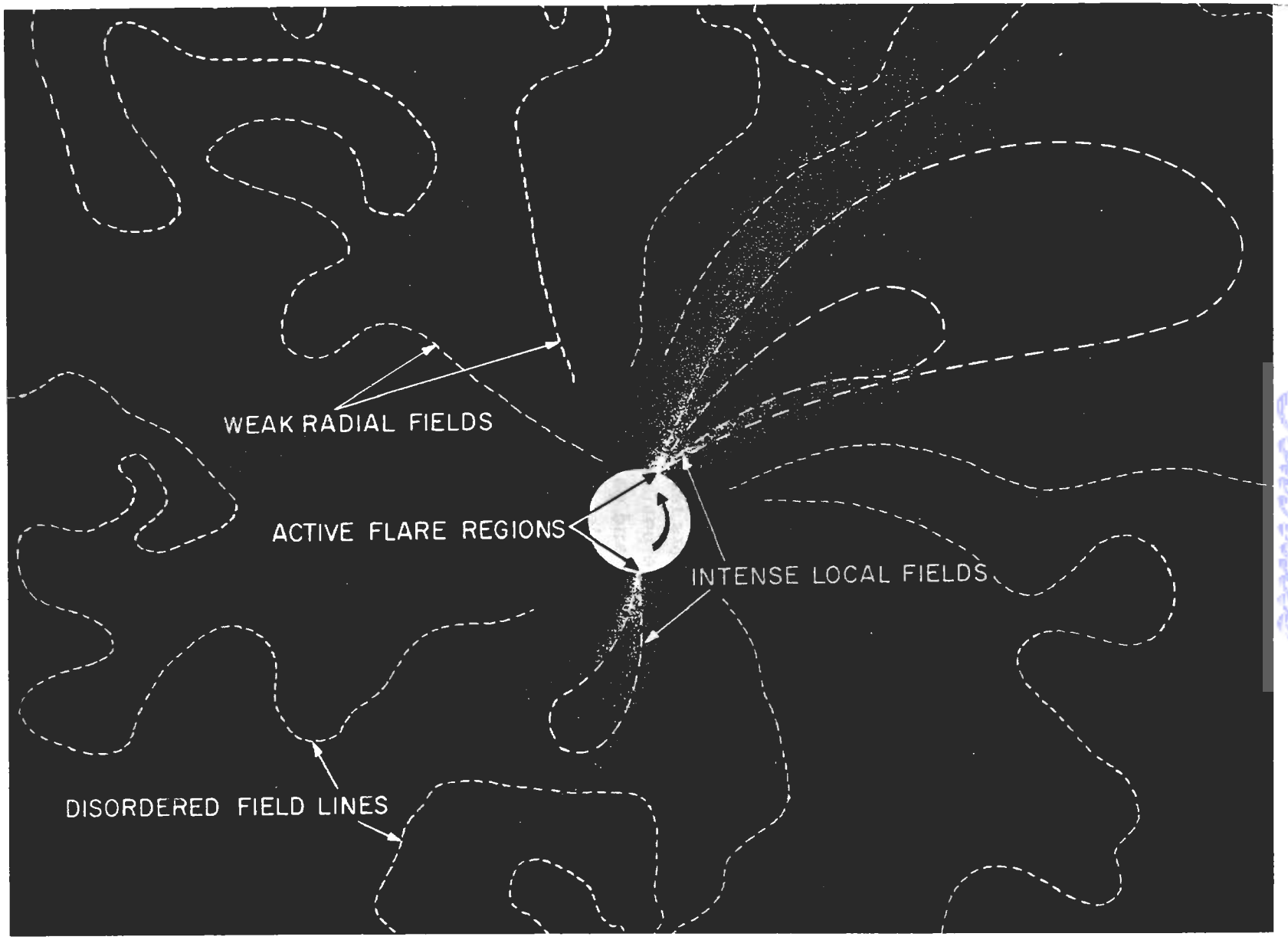


Figure 6. Theory of propagation of solar protons into interplanetary space along magnetic lines of force. Strong, ordered magnetic lines give rise to concentrations of proton streams of high magnetic rigidity (high energy); while the weaker, disordered lines contribute to the general diffusion of particles of all energy levels.

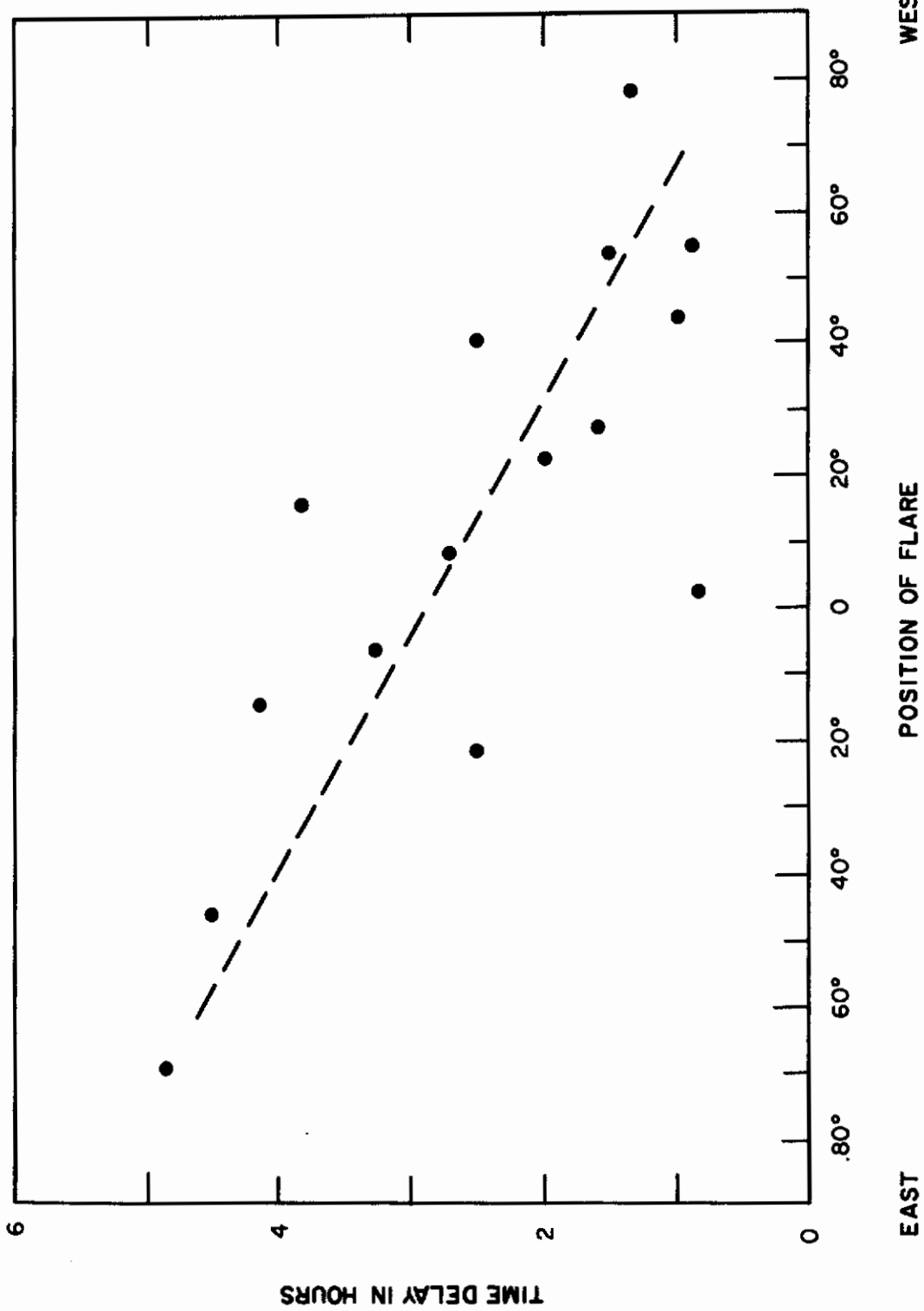


Figure 7. The time delay between visual observation of a flare and arrival of corpuscles as a function of flare longitude.

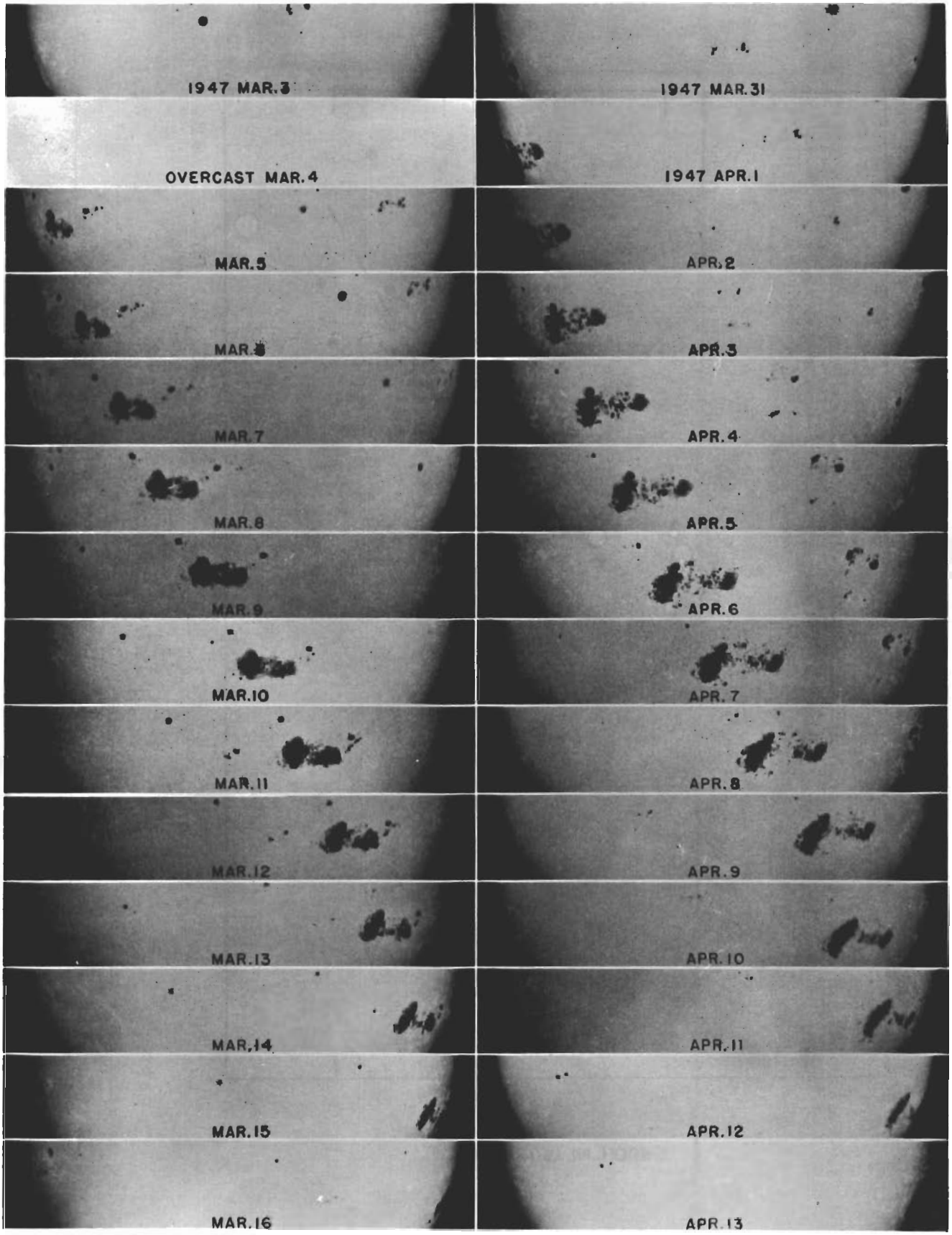


Figure 8. Photographs of the solar disk showing sunspot duration. (Mount Wilson and Palomar Observatories.)

Though not well understood, the mechanism of particle acceleration in flares is almost surely associated with intense magnetic fields around sunspots. Quite likely, rapid variations in these fields cause the ionized hydrogen to undergo acceleration. One explanation for the absence of electrons in the ejected radiation is that these particles are trapped in the sunspot magnetic fields where they subsequently lose their energy by synchrotron radiation, i.e., energy emitted in the form of electromagnetic radiation arising from centripetal acceleration of charged particles moving in a magnetic field. Radio emissions after flares lend credence to this idea[15].

Radiation intensities from these eruptions at times reach on the order of 10^6 particles/cm^2/sec and even for nonrelativistic flares the particles are known to have energies from about 40 to 500 Mev. Integral intensity spectra for nonrelativistic flare particles follow a power law such that the number of particles above a particular energy level is inversely proportional to the fourth or fifth power of energy. Expressed mathematically, this relation is[11]:

$$N_{(>E)} = \frac{C}{E^4} \text{ or } \frac{C}{E^5} .$$

Particularly note the variability in intensity as shown by the two exponents. This is an important aspect of flares--the fact that they are not all alike makes the problem of evaluating their effects more difficult. Direct measurements of intensities of particles in space have been limited to high energy flux because of the low energy cutoff in instrumentation sensitivity. Observed geomagnetic and auroral effects require[14] fluxes of as much as 10^{10} particles/cm^2/sec but for radiation effects, these particles may be ignored because of their low energy. In other words, for the same reason that they are difficult to measure, they are of little consequence as far as damage potential goes.

Because of the extreme variability in the energy/intensity spectra of these flares, curves for any particular flares could easily be given too much weight in the reader's mind. For this reason, the curves in Figure 9 are hypothetical examples, based on data from actual flares, which tend to show the range of intensity and energy which could reasonably be expected from a class 3+ nonrelativistic flare. Examples, as shown in Figure 9, are chosen because they illustrate the most severe known radiation environments from nonrelativistic flares. The initial radiation curves are simply plots of the E^{-4} and E^{-5} functions mentioned above; for a representative data point through which to extend the curves, 3.8×10^5 protons/cm^2/sec with energy greater than 23 Mev is used. This is the omnidirectional flux and corresponding energy level estimated[17] for one of the most intense flares on record, that of May 10, 1959.

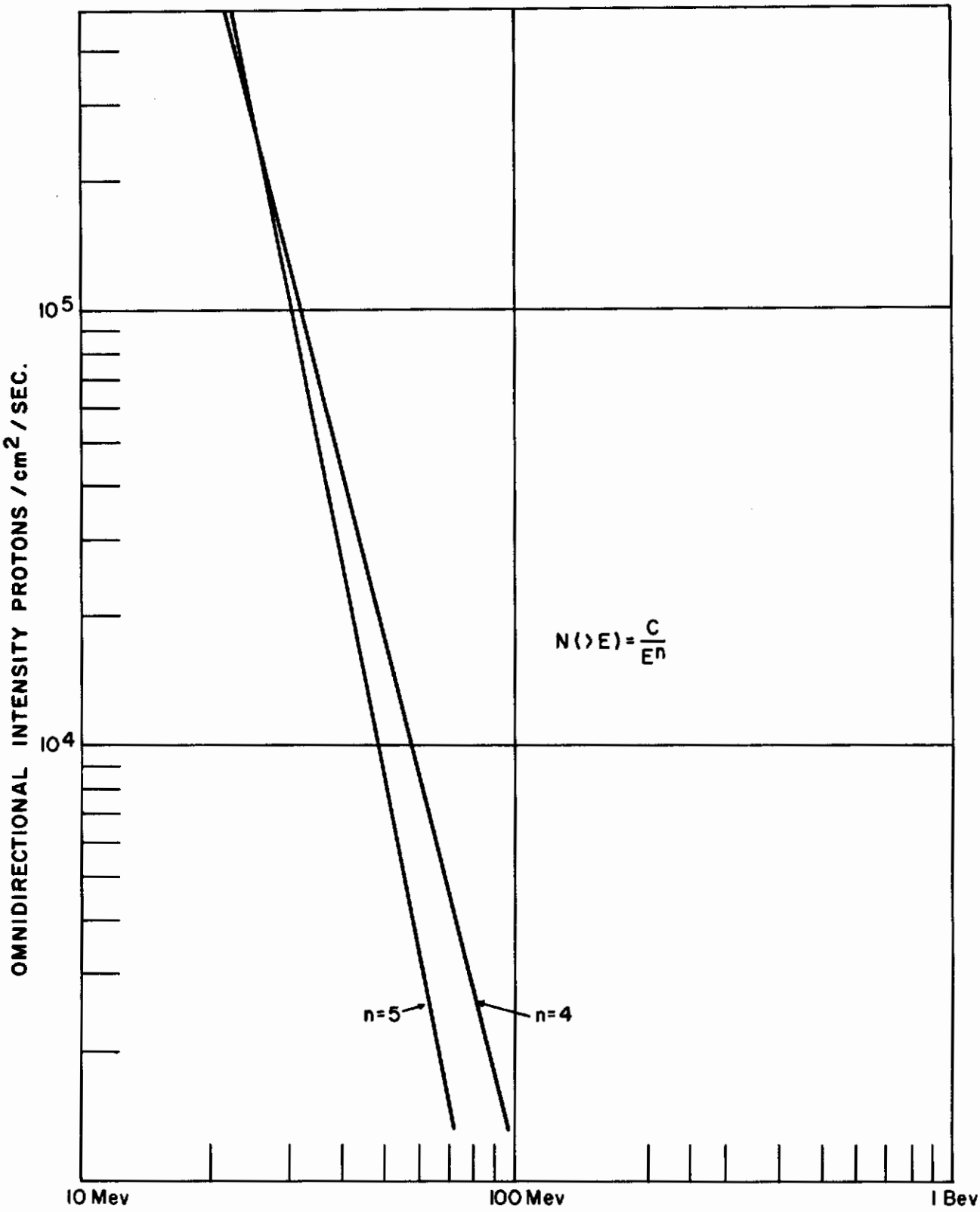


Figure 9. Nonrelativistic flare initial energy/intensity spectra. Based on assumed value of 3.8×10^5 particles/cm^2/sec with energy greater than 23 Mev.

Relativistic Flares

When solar flare corpuscular radiation is detected down to sea level, the occasion notes a truly remarkable event--the generation by the sun of particles in the galactic cosmic ray energy range. There are only six cases on record of events of this nature: February and March 1942, July 1946, November 1949, February 1956, and May 1960. The flare on February 23, 1956, was the largest ever recorded and has been extensively studied and reported in the literature.

Since the February 1956 flare was so well documented, and because it represents the greatest known radiation environment from relativistic flares, it serves well as a model for this type of event. As observed on the earth, the sequence of observations was:[18]

(1) Optical and radio outbursts were followed almost immediately by the initial particles of relativistic energy, from the preferred direction of the sun.

(2) Shortly thereafter particles of lesser energy began arriving isotropically, a condition which soon included the high energy particles.

(3) From the peak intensity at 0342 universal time, there was a gradual drop in radiation as shown in Figure 10. The counting rate of this figure is of secondary radiation created in the atmosphere by flare primaries and therefore shows the trend in intensity decay in space, but not the counting rate above the atmosphere.

The flux from this flare was probably all protons and may have reached intensities as high as 10^5 p/cm^2/sec, including all energies, and 10^3 p/cm^2/sec with energy greater than one Bev. Decay in intensity followed a relation given by:[13]

$$I = I_0 \left(\frac{t_0}{t}\right)^2 ,$$

where I_0 and t_0 are intensity and time one hour after the flare began. Expressed another way, the flux diminished in proportion to time^{-2}, or I/t^2. Probably at some time later the flux decay was proportional to $I/t^{1.5}$.

An integral energy/intensity spectrum for typical relativistic flares is shown in Figure 11. Here again, for purposes of presenting

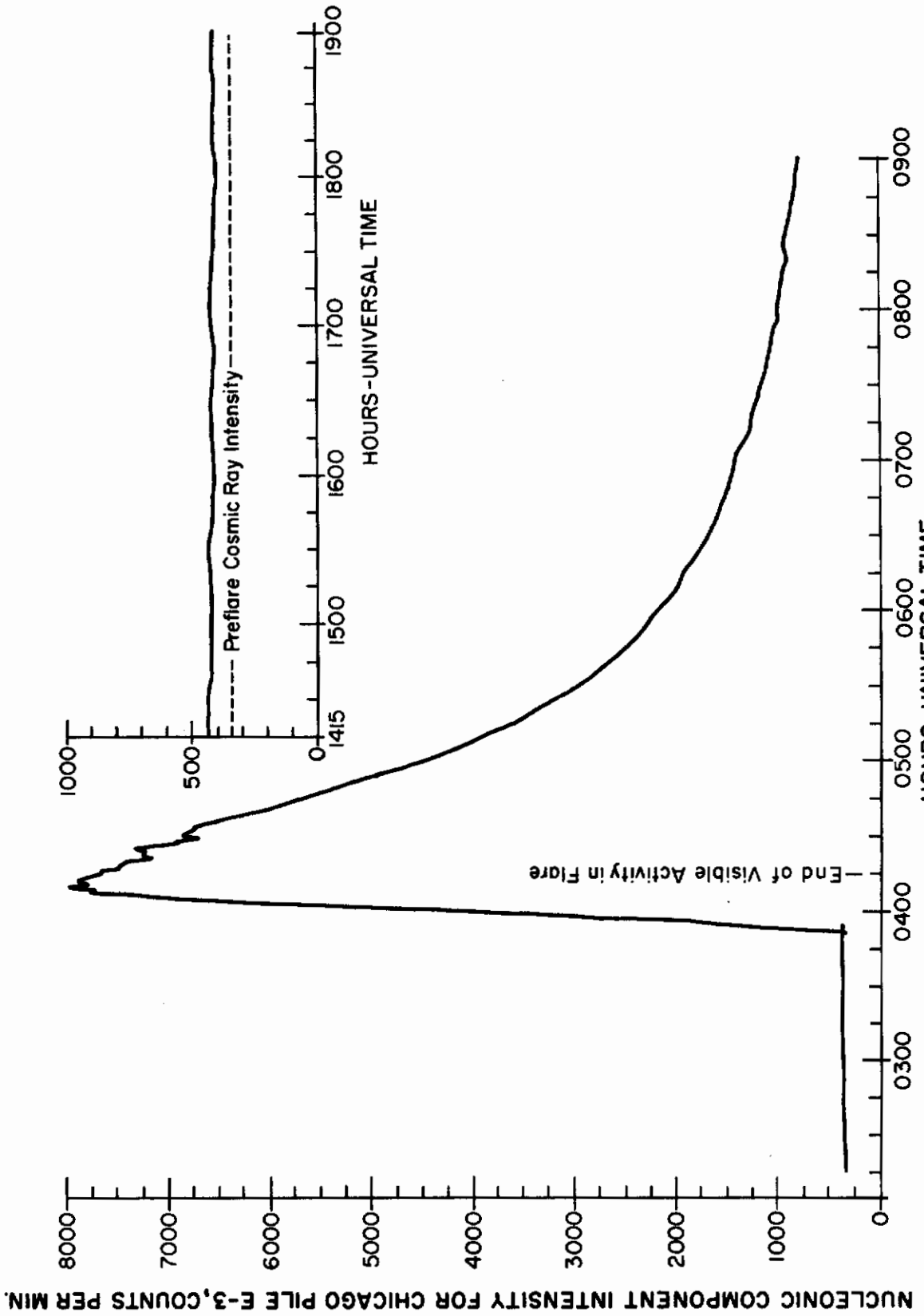


Figure 10. Counting rate of a sea-level monitor during the large relativistic flare of February 23, 1956.

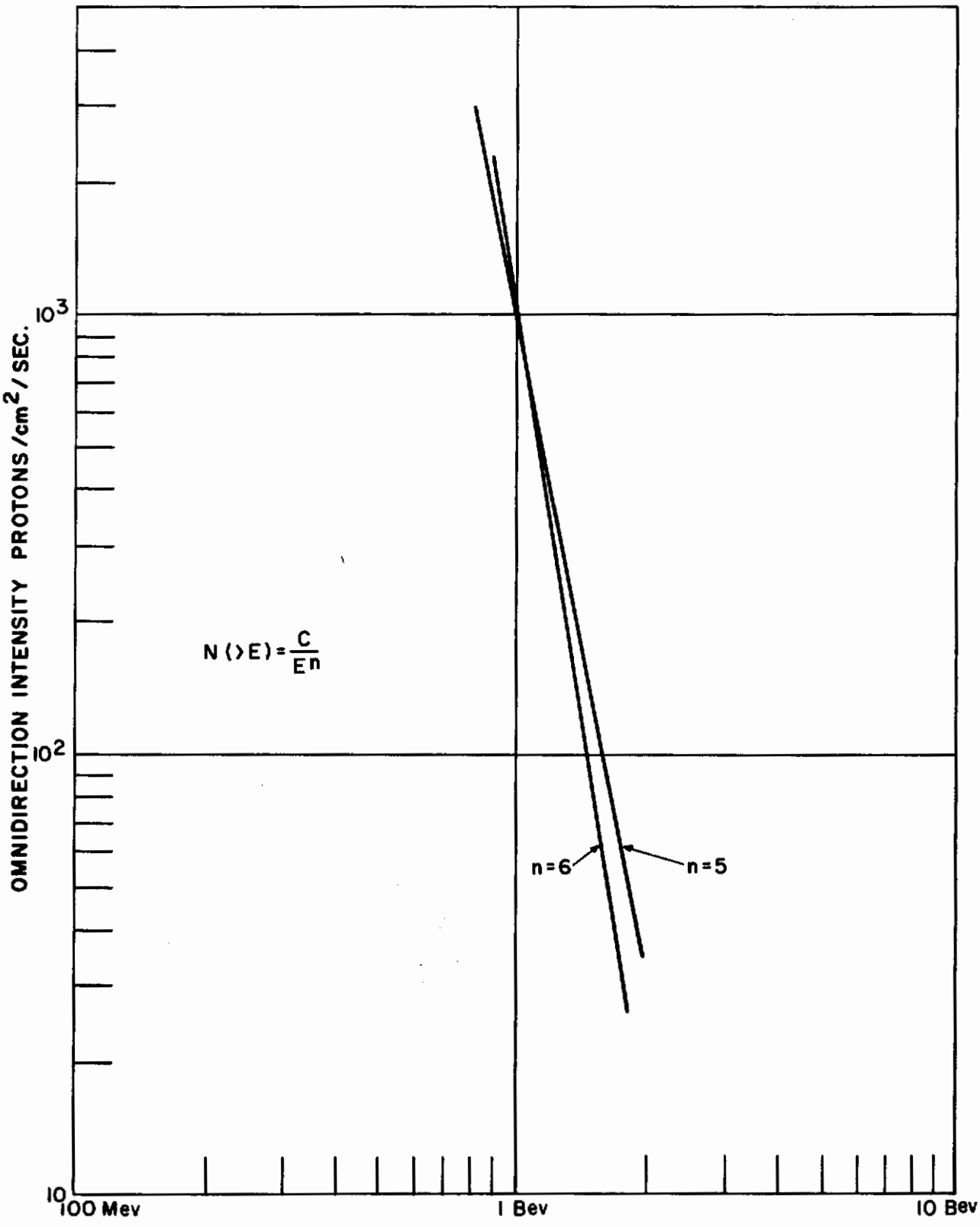


Figure 11. Relativistic flare initial energy/intensity spectra. Based on assumed 10^3 particles/cm^2/sec with energy greater than 1 Bev.

spectra which are representative, the curves shown are theoretical but based on observed data from a specific large relativistic flare. Taking the value[11] of intensity 10^3 protons/cm^2/sec with energy greater than one Bev as a likely estimate, relativistic flare spectra are given for the expression:

$$N_{(>E)} = \frac{C}{E^5} \text{ or } \frac{C}{E^6} .$$

Particles with energies in excess of 15 Bev, and probably in excess of 20 to 30 Bev, were produced in the 1956 flare[19]. This is the upper limit which should apply to the spectra of Figure 11. Very little is known about the spectra of relativistic flares below about one Bev. This is most unfortunate because it leaves in question the magnitude of what may be the greatest radiation hazard in space; if the particle spectrum of such a flare should be as steep at lower energies as at those above one Bev, the radiation intensity would be enormously high at energies very difficult to shield against. Extrapolations below about one Bev are given in the literature which show a decreasing slope with decreasing energy.

FLARE RADIATION DOSAGE

It is impossible to say what exact biological damage can be expected from solar flare corpuscles without knowing: (1) the flare radiation environment, including composition, intensity, energy, and variations of these with time and direction; and (2) the shielding available, including type of material, thickness, and placement geometry in relation to the shielded subject and incoming radiation. As we have seen, the first of these general requirements, knowledge of the environment, is only partially known. The second, available shielding, is a design problem as yet unsolved because the shielding weight capacities of future vehicles are not known; the shielding ability and optimum use of all likely materials are not completely known; the biological effect of different types of radiation is not completely understood; and of great importance, the short-term and long-term doses which can be tolerated acceptably for particular missions is an arbitrary quantity dependent largely on philosophical considerations.

For the above reasons, discussions of flare dosages must by necessity be predicated upon a number of assumptions which then apply to specific cases but are questionable for general anticipation of radiation damage which the future space traveler will be likely to receive. A brief insight into the problems follows, illustrated by a number of specific examples.

Typical Results

In order to estimate the radiation dose from a flare, it is necessary to make assumptions or have given: (1) the particle spectrum, (2) the shielding, and (3) the biological effectiveness of the radiation. At present about the only valid approach is to assume values of these parameters. An analysis conducted in this manner is found in reference 17. The basic assumptions in this report are probably as representative and as valid as can be made at this time, and, consequently, the results are included here. It should be emphasized that these results are rather speculative, but they do provide at least an order of magnitude measure of flare hazards.

The flare of May 10, 1959, is the model chosen for the radiation environment. This particular flare was one of the most intense on record. Because of its many desirable properties of carbon and its likelihood of being selected for shielding in space vehicles, it is the shielding material specified. (The shield geometry chosen is a sphere with an inside radius of 90 centimeters. This confinement of about three feet constitutes strictly an emergency shield.) The radiation is assumed to consist of incident protons and secondary neutrons created in the carbon; a relative biological effectiveness (RBE) factor of 10 for protons is included in the computations for REM, a questionable value which will be discussed later. Once a shielding material and geometry are selected, about the only degree of dose control available to designers is shield thickness; plots of this variable against REM are of particular interest, and one such curve is included.

An integral energy/intensity spectrum for the May 1959 flare under discussion is given in Figure 12, derived from reference 20. The ordinate expresses omnidirectional intensity rather than unit solid angle intensity, an assumption based on the isotropy of flare radiation in space away from geomagnetic influences. Extrapolation below 110 Mev is indicated by a dashed line. A spectrum such as this provides a basis for determining the radiation constituents which penetrate a given amount of shielding.

By integrating the flux at particular energy levels for the duration of the bombardment by flare corpuscles, assuming t^{-2} or similar decay in intensity, a curve of dose as a function of cutoff energy can be derived; Figure 13a is such a curve. Dose has been calculated in REM (assumed RBE of 10) as a function of shield cutoff energy, i.e., the energy of the lowest energy proton able to penetrate the shield. From curves of dose versus cutoff energy such as the hypothetical example shown in

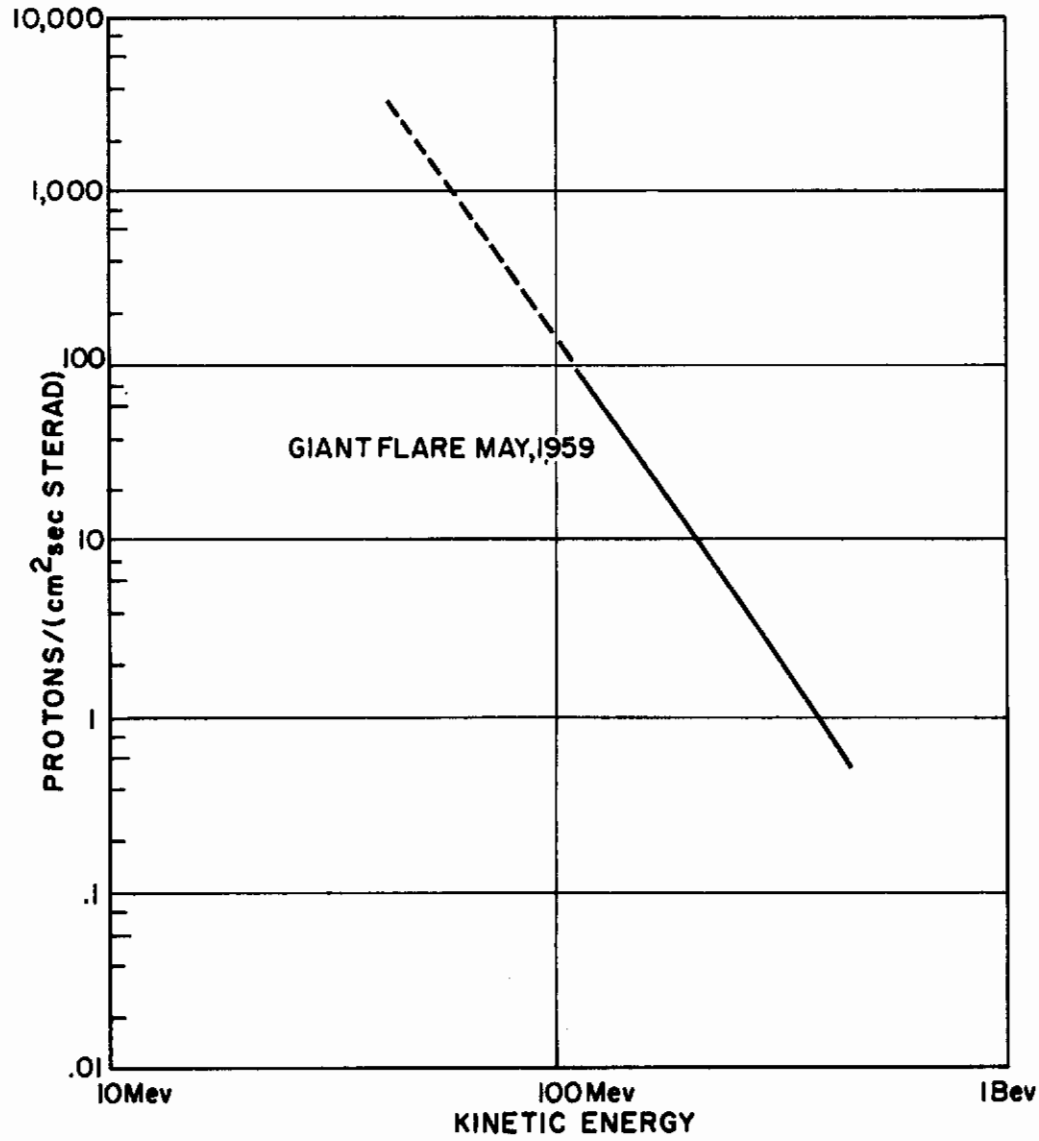


Figure 12. Integral energy/intensity spectrum for the May 1959 flare.

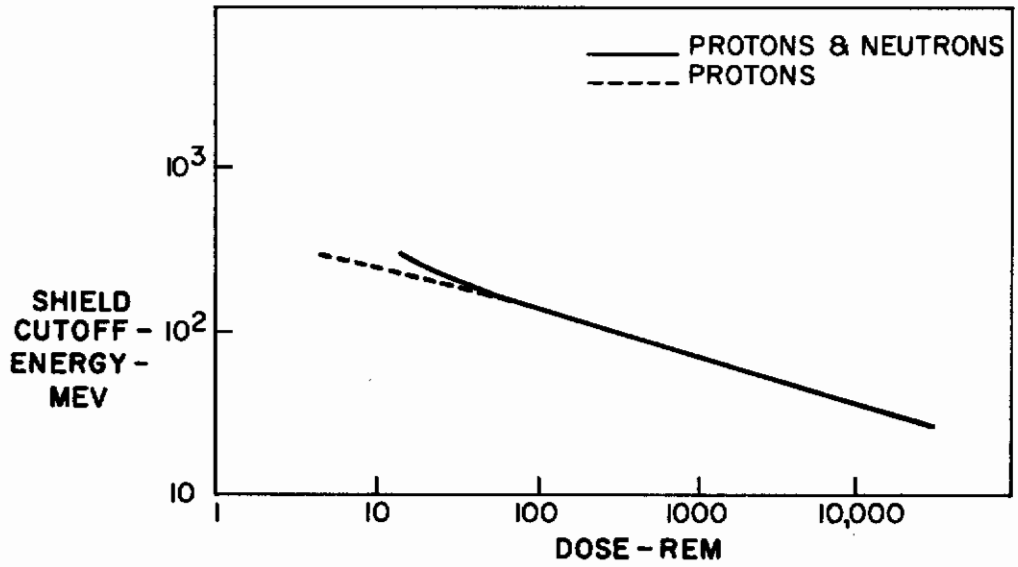


Figure 13a.

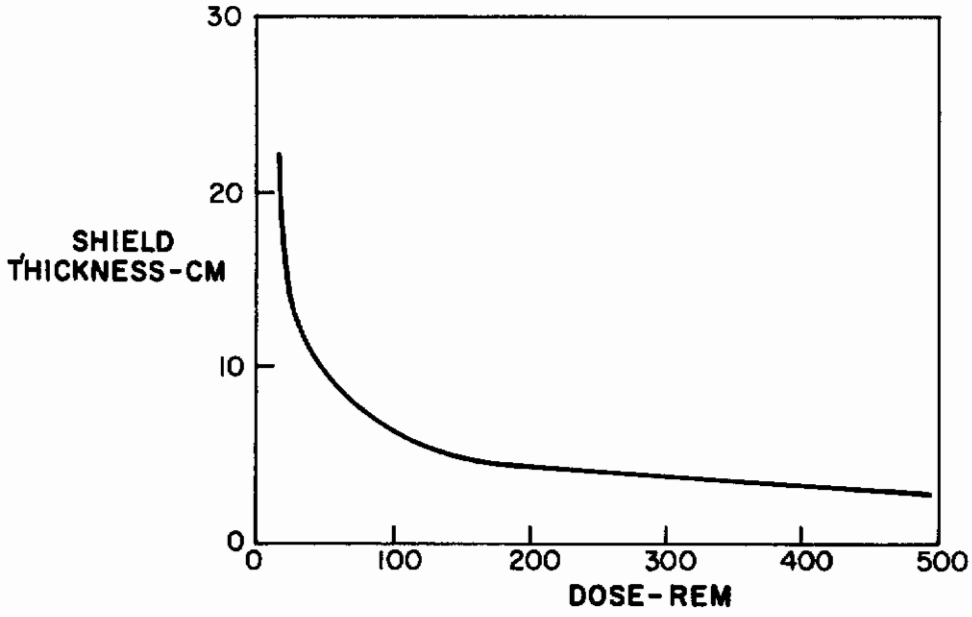


Figure 13b.

Figure 13. Shield cutoff energy and shield thickness as a function of dose.

Figure 13a, shield thicknesses which correspond to particular dosages may be calculated; these parameters are shown hypothetically in Figure 13b.

Only a cursory inspection of Figure 13b is necessary to conclude that an intolerable dose can be prevented only by thicknesses which result in very heavy shields. The cramped spherical design of this analysis would never be more than an emergency retreat. As an example of the time a crew member would be required to take refuge, note the rate of accumulation of dose in Figure 14. This is a curve of the fraction of total dose from a typical large flare as a function of time from reference 21. About half of the dose can be expected within the first hour, while 90 percent of the dose should be over in perhaps five hours.

Effect of RBE

Though the above results obtained in a typical analysis in the literature (dosages in REM) appear ominous, they are probably more pessimistic than necessary by an order of magnitude because of the inordinately high selected value of RBE = 10. It is quite probable that the protons in question should be assigned RBE values of little more than one. Now, this is an important point and should be explained.

First, RBE values of ten apply to protons in an energy range below that of practical concern to crew members in space. Particles of higher energy tend to pass through tissue, expending less of their energy in a given length. A measure of this linear energy transfer (LET) can be expressed in the number of ion pairs produced in tissue per unit length, say in microns. The manner in which LET varies with proton energy is shown in Figure 15a, taken from reference 22. It is obvious from the curve that transfer of energy (i.e., ionization) is greatly diminished at energies above one Mev. Figure 15b, also from reference 22, shows corresponding RBE values over a range of proton energies. Since a particular proton in traveling through matter ionizes at a changing rate, there exist instantaneous RBE values, as indicated. Its mean RBE taken over a whole path is also shown. It can be seen that high RBE values occur in a limited, and low, energy range. Beyond about ten Mev, values of RBE very nearly equal 1.0.

PREDICTION OF PROTON EVENTS

Recognition of the flare-produced radiation hazard has greatly increased the importance of prediction methods. Previously, flare prediction was prompted almost entirely by the practical needs of radio

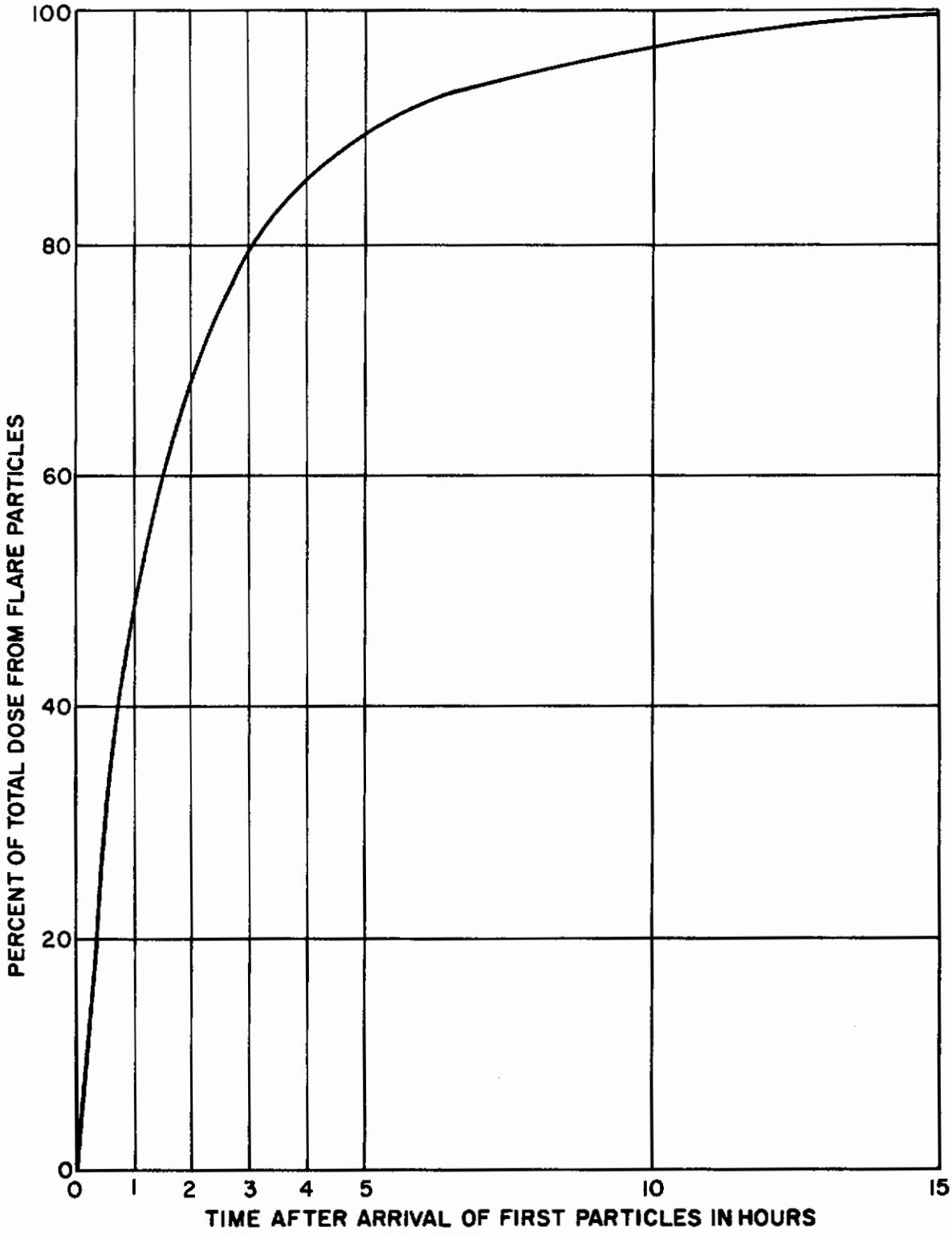


Figure 14. Fraction of dose from a flare as a function of time. (Typical t^{-2} dependence.)

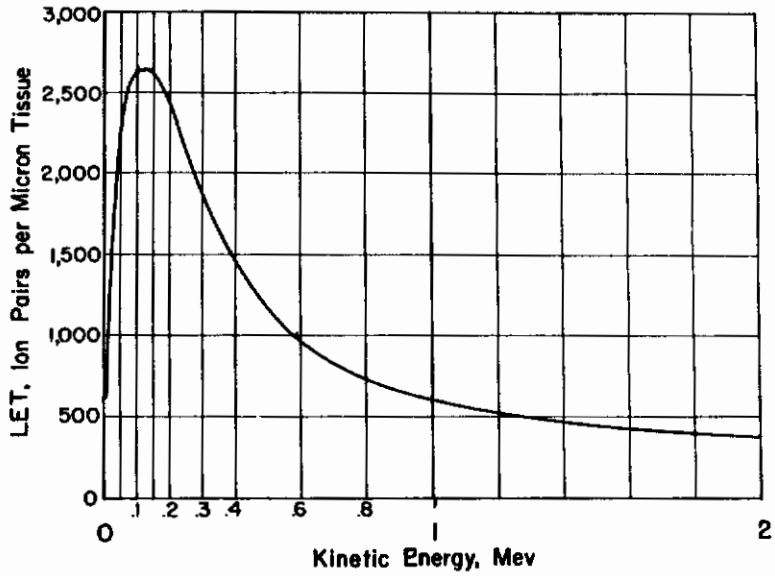


Figure 15a.

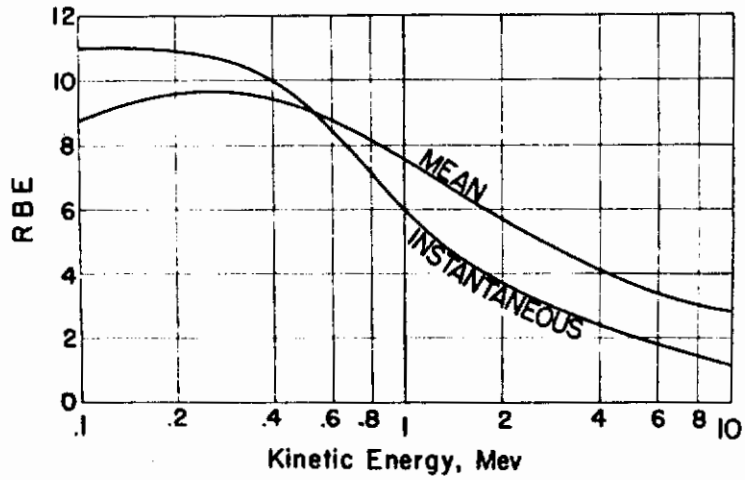


Figure 15b.

Figure 15. LET and RBE as a function of proton energy

communication because of the effect of solar corpuscles on ionosphere conditions. There are two distinct aspects to forecasting the occurrence of proton events: (1) The long-term or average number which can be expected over a given period; and (2) the short-term or particular time when a flare is likely to appear. Importance of the first aspect lies in long-range thinking such as space craft design and mission planning. For example, if it were fairly certain that flares would be infrequent in, say ten years, then a more optimum distribution of shield weight for space vehicles of that time could be devised. Perhaps this would be manifest in a more confined emergency shield since it would be used less frequently; the weight saved then would be available for other purposes in the never-ending compromise between weight and performance. Short-term predictions are important as warnings to those in space to return or make preparations to use emergency shields; also, warning of an impending flare would allow abort decisions to be made for missions nearing the launch phase.

Correlation Between Proton Events and Sunspots

Sunspots are good indicators of many kinds of solar activity, and in fact the commonly accepted criterion for activity is simply the sunspot number. But an active sun, per se, does not mean that flare-produced high energy particles will definitely be in evidence. Sometimes the sun may be very active with respect to prominences, plages, and even flares, yet there will be no noticeable corpuscular radiation outburst. For prognostic purposes, it is highly desirable that any correlation between easily observed spots and proton events be discovered.

Overall, however, there appears to be a direct relation in the number of solar proton events and the number of sunspots. This conclusion is based on a rather limited amount of data, from a statistical standpoint, since it was drawn from the events covering only one eleven-year solar cycle. Figure 16 is a plot of both these items--the correlation shown here is quite strong in spite of the limited data. The implication is clear that solar proton emissions are infrequent during times of low sunspot number, and conversely that they are numerous during periods of high sunspot number.

Long-Term Prediction

Since the correlation between particle flux enhancements and sunspots appears definite on a time average, predictions of the latter can serve as forecasts of future radiation hazards. Records extending over many years have established the approximately eleven-year periodicity in

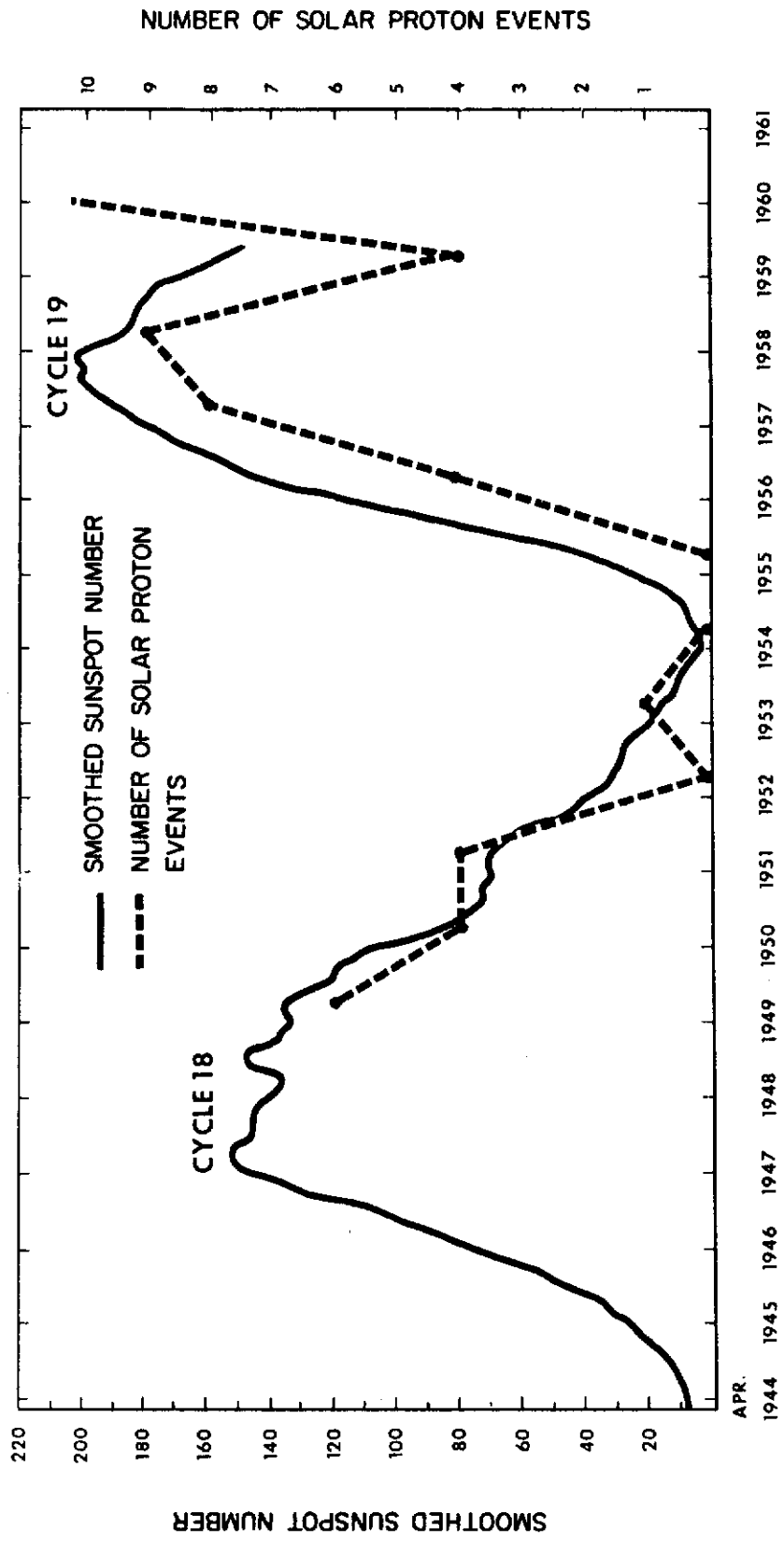


Figure 16. Correlation between sunspot number and solar proton events.

sunspot number. This provides a very good first-order term in the solar cycle. But the height of any particular peak cannot be so easily predicted. There is thought to be a cyclic variation with a period of about 170 to 180 years. Due to uncertainty, even if this variation exists, the next cycle reaching maximum in 1969 cannot be forecast either as the high point in the long-term variation or as the beginning of a new long-term cycle with a low maximum number. Should the next eleven-year cycle (number 20) result in a very high maximum, the outlook beyond 1975 will be more promising with respect to radiation hazard for fifty years or so[12].

Statistical treatment of the sunspot record (Figure 2, page 9) is not as reliable a method as is necessary for advance planning, but it is of interest that one such analysis[23] resulted in a probability of 30 percent that the 1968 peak will be higher than the 1958 maximum. A conclusion from that same analysis was that there is a 75 percent probability that the next smoothed peak sunspot number will be in the range of 110 to 160.

Another method of foretelling the probable course of a particular eleven-year cycle is thought to be more reliable than the purely statistical approach. It has been found that a plot of sunspot numbers from the beginning of a cycle minimum tends to rise early in the new cycle in a manner which indicates whether or not the upcoming maximum will be high or low. In Figure 17 the four most recent cycles are plotted[2]. By this method, it is thought that the trend at 18 months from minimum establishes the type of cycle, whether high or low. Figure 17 shows that this type of forecast is not infallible, yet it does look promising. Using this method, cycle 20 will be predictable, with reservations for uncertainty, in late 1965.

Short-Term Prediction

The problem of prediction of solar proton events in immediately approaching times is quite different than the problem of long-range prediction. Average behavior is, of course, a poor means of foretelling when a particular outburst will occur, though it is a good indicator of likelihood of occurrence over a given, preferably lengthy, period. The sun does provide a few clues to its future tendencies by direct observation, so studies have been made to determine if any observational data can be interpreted as predictors of flare-produced particles.

In regard to an average or statistical rationale for forecasting more immediate proton events, there has been suggested a possible seasonal effect, notably the infrequency of events between October and April.

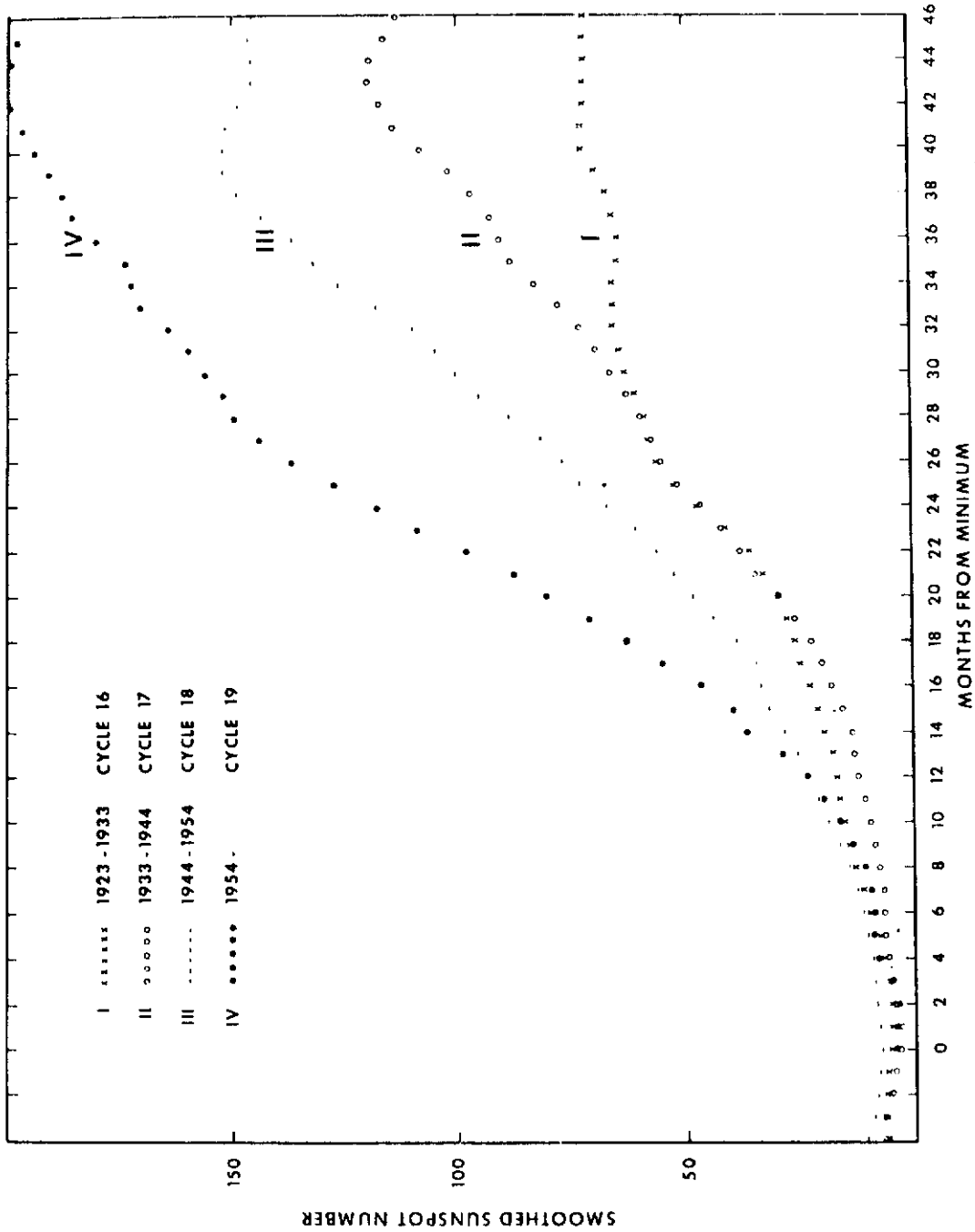


Figure 17. Four recent solar cycles. The sunspot number at 18 months is thought to show the tendency toward a high or low peak.

Reference 24 suggests that there may be: (1) an eleven-month cycle in the peak number of events; (2) a semi-annual variation which has maxima in March and September; and (3) a maximum occurrence on the average near the September equinox and a minimum around December-January. These are admittedly conclusions based on weak evidence. Observations in the next few years should either dispel or enhance this idea, but for the present it should be given little weight.

Though high spot numbers are associated with frequent flares, they are not definite indicators that a proton event or even a flare is on the verge of birth. Other spot features that are favorable to the occurrence of large flares but which are not certain indicators are: spot groups in which the number of spots is fairly great, large size of at least a few spots, considerable penumbral area, and rapid increase in spot number[2].

A promising method of flare warning is described in reference 2. It depends on a careful watch of sunspots to measure their penumbral area. The penumbra of a sunspot is the transition region between the photosphere and the darkest spot area--it is characterized by a filamentary structure darker than the photosphere but lighter than the spot itself. Figure 18 is a photograph of a large complex spot group. The penumbral region is clearly evident in this high magnification photograph. Penumbral areas can also be seen in some of the photographs of Figure 8 (page 24).

Reference 2 describes an analysis of approximately forty solar proton events and their parent flares. It was found that when sunspots developed large penumbral areas they were probable sources of flares. Though this criterion is not always a certain indicator, the correlation is high, and the method appears to be much better than any other for giving advance warning of large flares. Other possibilities, such as those based on radio and coronal optical emissions, have not been fully explored, but do not offer grounds for optimism for anticipating corpuscular radiation hazards.

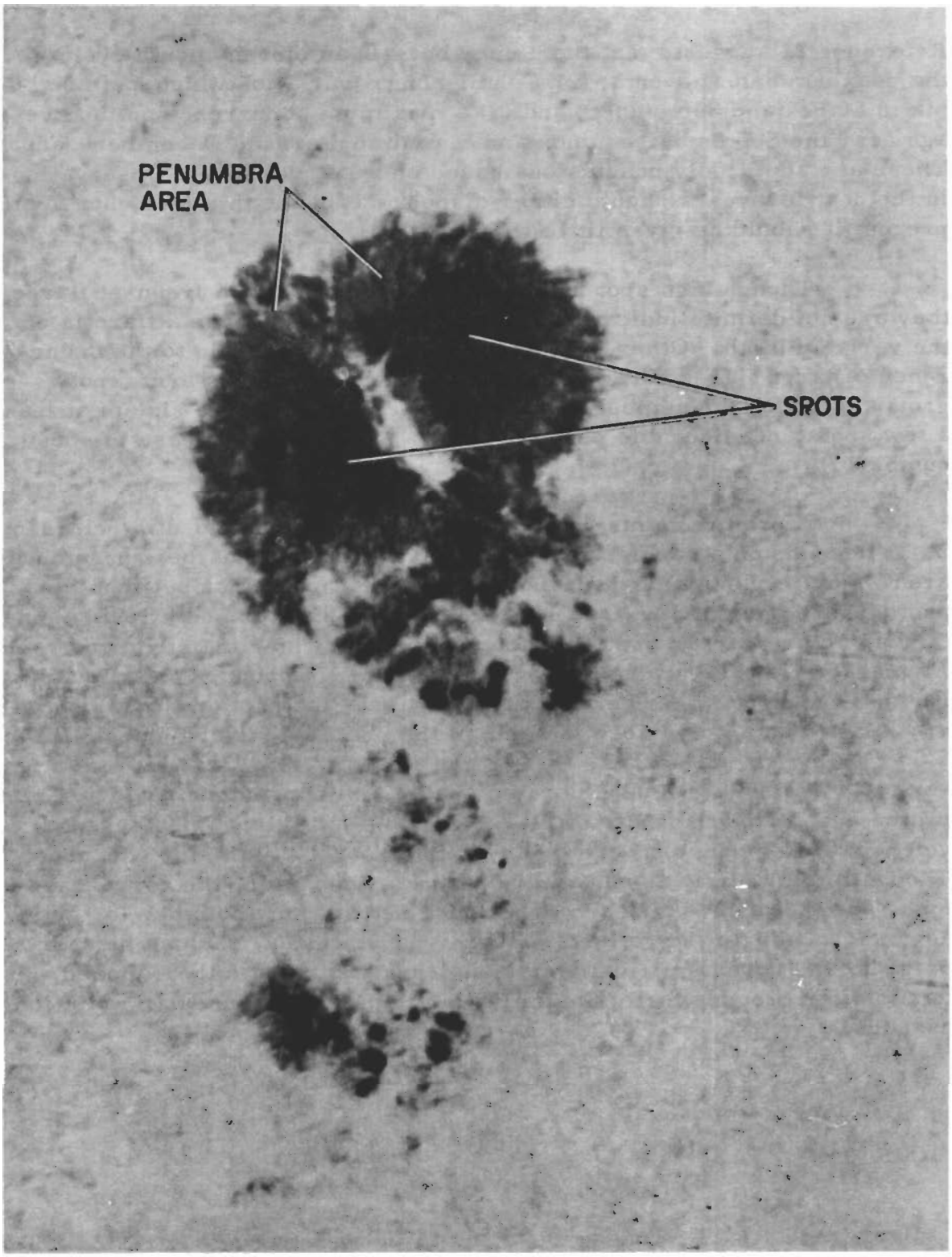


Figure 18. Sunspot group. Large penumbral areas may indicate that a flare is imminent. (Yerkes Observatory.)

SECTION II

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SECTION III

TRAPPED PARTICULATE RADIATION ABOUT THE EARTH (The Van Allen Belt)

HISTORY

In May 1958, Dr. J. A. Van Allen of the State University of Iowa announced the discovery of belts of high intensity radiation about the earth. His discovery was the result of measurements made possible by the Explorer I and Explorer III satellites. The presence of the radiation belts was confirmed by satellites Pioneer III, Sputnik III and Mechta and finer measurements were secured with instrumentation contained in the Explorer IV, VI, and VII satellites. Additional data are being secured in other missile programs.

Early theorists such as Stoermer, Poincare, and Alfven had suggested that charged particles might be trapped in the earth's magnetic field but it was not until Dr. Van Allen's analysis of Explorer III data that the theory was fully confirmed. Later, the Argus experiments in August and September of 1958 demonstrated that movement of electrons, produced in the beta decay of fission fragments produced by high altitude detonations, was controlled by the earth's magnetic field[37]. Previous to these experiments, rocket tests had disclosed low energy particulate radiation at high altitudes in the northern and southern auroral zones. These tests were made in the period 1953 to 1957.

As a result of the total of these findings, it is evident that in addition to the atmosphere of gas surrounding the earth, there is a belt of charged particles girding it. A vast region about the earth's atmosphere is occupied by these particles which at low latitudes extend from 8 to 12 earth radii from the geomagnetic axis on the sunlit side of the earth. While this protonosphere, or magnetosphere, or electronosphere, or geocorona, as the region has been called, is a region of potential danger to the unshielded astronaut, it does represent a region where the earth's magnetic field provides a shield for the atmosphere against solar discharges. Present knowledge of the region is still limited, particularly in the low energy portion of the radiation spectrum.

THEORY

The discovery of the radiation in the space about the earth was followed by a period of intensive investigation and analysis of the

phenomenon. The results of succeeding measurements provided a better understanding but did not establish conclusively either the mechanism by which the belt is maintained or the precise composition.

As a result of observations from the Pioneer III probe, Professor Van Allen stated that there were two distinct, widely separated zones of high intensity[22]. He cnnjectured that the outer zone might be due to solar plasma and the inner zone to albedo neutron decay products, or possibly to selective radial diffusion of particles in the inhomogeneous geomagnetic field according to their respective magnetic rigidities or according to a combination of the sign of the electrical charge and their magnetic rigidity.

INNER ZONE

The observed spectrum and the composition of the particles in the inner zone as determined to date are relatively consistent with the cosmic ray albedo decay hypothesis of origin. This envisions that primary cosmic rays entering the earth's atmosphere strike the nuclei of atmospheric molecules causing the nuclei to disintegrate. Since neutrons are released isotropically in these disintegrations, a certain fraction of the neutrons will travel out from the earth. These outward traveling neutrons represent the cosmic ray albedo. Being uncharged, the neutrons travel along straight lines. With a half-life of about 12 minutes or a mean life of about 20 minutes, a free neutron is unstable with respect to beta decay into a proton, an electron, and a neutrino. The electrons are released isotropically and have an energy spectrum with a peak at about 300 kev and an upper limit of 780 kev. This spectrum is essentially independent of the energy of the parent neutron. On the other hand, the protons which are released travel essentially in the same direction as the parent neutron and have an energy closely related to the parent. This in substance is believed to be the origin of the charged particles trapped by the earth's magnetic field.

OUTER ZONE

The source of particles in the outer zone is also open to debate. A majority of authoritative opinion contends that the main source of these particles is the sun; particles ejected by the sun travel outward as a solar plasma or wind. In the sphere of influence of the earth, the solar plasma perturbs the geomagnetic field. In the ensuing reaction, there is a transfer of energy and particles are trapped by the geomagnetic field.

Significant changes in the outer zone have been detected as a result of solar disturbances. After the great magnetic storm of

September 4-5, 1958, there was a substantial increase in the average intensity of energetic electrons in the outer zone. Time variations have been observed in both the intensities and the energies of the relatively low energy particles in the outer zone. These have been intimately connected with the occurrence of magnetic storms. Aurorae are also associated with these disturbances. Contrariwise, in the inner zone, the intensity of the particles has not been observed to vary significantly with these phenomena.

Some doubt has been cast on the solar origin theory. In reference 3, the following case in opposition is presented:

1. During the very active phase of magnetic storms when the dipole character of the geomagnetic field is disrupted, a decrease in radiation counting rate is observed in the outer zone.

2. After the active portion of the magnetic storm is over, the observed particle counting rate increases by several orders of magnitude. This is at a time when the regular pattern of the geomagnetic field is restored so that entry of any but very energetic particles such as cosmic rays is not reasonable.

3. The lifetime of particles in the rarified region at several earth radii is a year or more; yet the solar injection theory envisions the disappearance of many particles in a few days. Also the Geiger tubes in the Pioneer IV deep space probe failed to detect any energetic particles in the region beyond 15 earth radii over a period of some 76 hours.

Accordingly, it was contended that violent changes in the geomagnetic field rather than any radical changes in the number of trapped particles give rise to the varying counting rates and that the particles in the Van Allen belt are solely the result of neutron decay.

In opposition to this stand, it has been pointed out that if aurorae are a result of a discharge of radiation along a line of force in the atmosphere in the polar regions, a theory which has been generally confirmed and accepted, the average energy dissipated is several orders of magnitude greater than would be available from neutron decay. A comparison of the measured electron flux along a line of force in the outer radiation belt with calculations that assume all electrons are

injected by neutron decay, as reported in reference 27, showed that the distributions were quite different at intermediate and low altitudes.

A conclusive answer concerning the origin of the electrons in the inner and outer belts and the manner of their injection must await further experimentation. Acceleration of low-energy electrons by the geomagnetic field would appear to be a strong possibility with the particles coming both from the sun and from the earth's atmosphere.

SHAPE AND COMPOSITION

What is indisputable as regards the shape of the belt of particulate radiation is that it extends about the geomagnetic equator for a great distance outward in relation to the earth's diameter. That the gross shape of the belt is governed by the geomagnetic field is also not in question. These are facts which have been confirmed by all existing evidence. In Figures 19, 20, and 21, the plotted observations show the variation of the intensity of the inner zone with longitude, geomagnetic latitude, and with altitude. In reference 26, the variation with longitude is attributed to the displacement of the magnetic center of the earth from its geometric center. The exact distribution of particles within the belt, their energy and intensity, are variable and are still being studied.

In general terms, the particulate radiation belt can be depicted as shown in Figure 22. If the energies of the particles are used as a general criteria, it can be said that there are two radiation regions in co-existence as illustrated in Figure 23; an inner belt with a high intensity of penetrating protons and an outer belt with a high intensity of penetrating electrons. The division into regions is arbitrary. In fact, the regions are intermingled and cannot be separated so it is more realistic to picture the region as a single, but inhomogeneous, belt with a peak intensity of highly energetic radiation at somewhat less that two earth radii from the geomagnetic axis and a peak intensity of particles somewhat less energetic about 3½ earth radii out from the axis. The region about the first peak is called the inner zone or proton belt; the region about the second peak is called the outer zone. At least one major discontinuity exists on occasions between these peaks as illustrated in Figure 23. The radiation levels as recorded on the incoming portion of pass 27 of satellite Explorer VI on August 27, 1959, show three distinct radiation regions at approximately 8,500 km, 10,000 km, and 11,500 km from the earth's center. The relative intensities shown here are not significant because they must be considered in relation to point of observation and the magnetic lines of force. The lower limit of detectability of the instrumentation was about 16 Mev for protons and about 2 Mev for electrons directly. Further, while the ionization chamber had an essentially

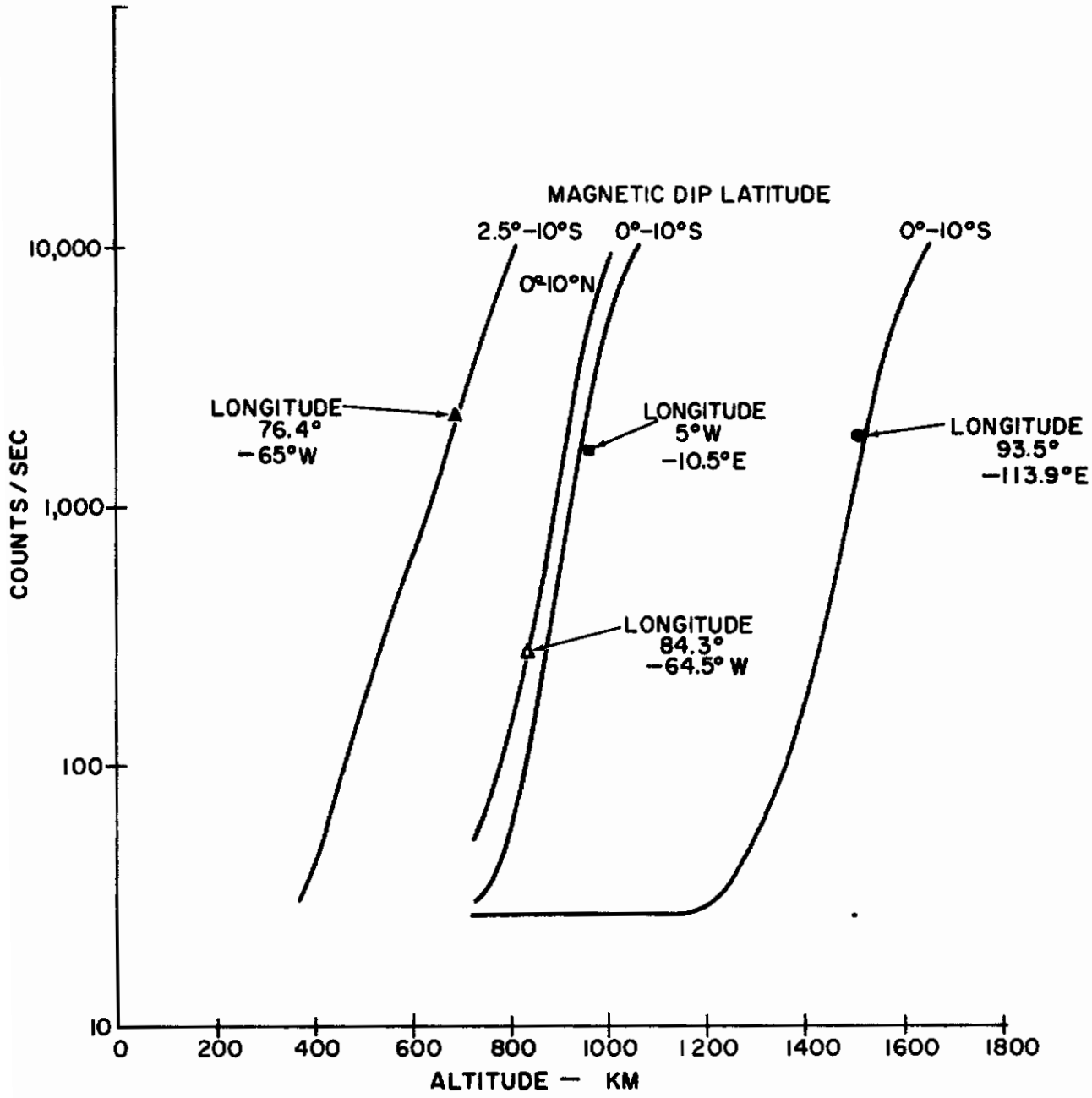

Figure 19. Variation of radiation intensity with longitude.[26]

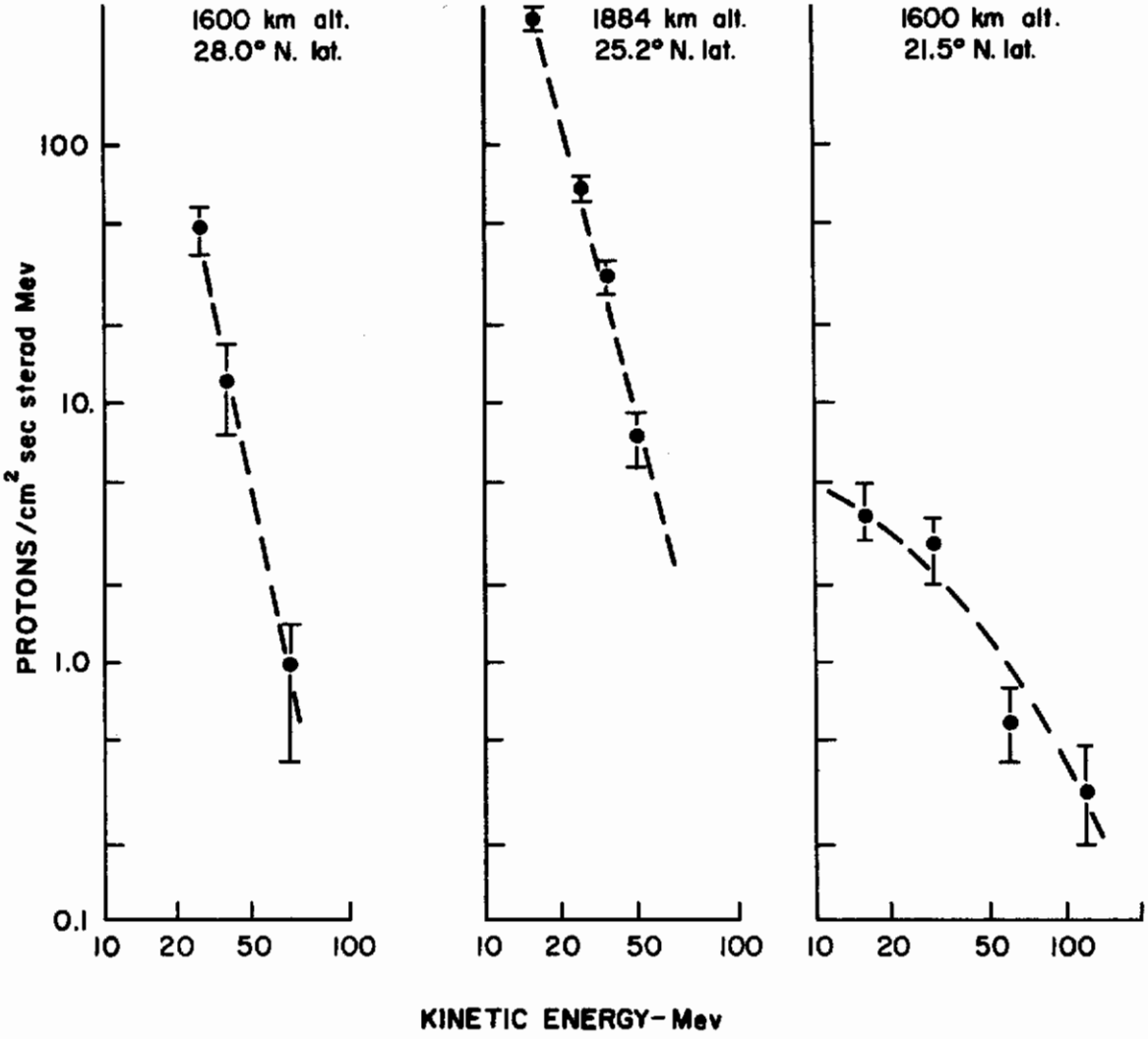

Figure 20. Differential energy spectra of protons in the inner Van Allen belt showing variation with latitude.[17]

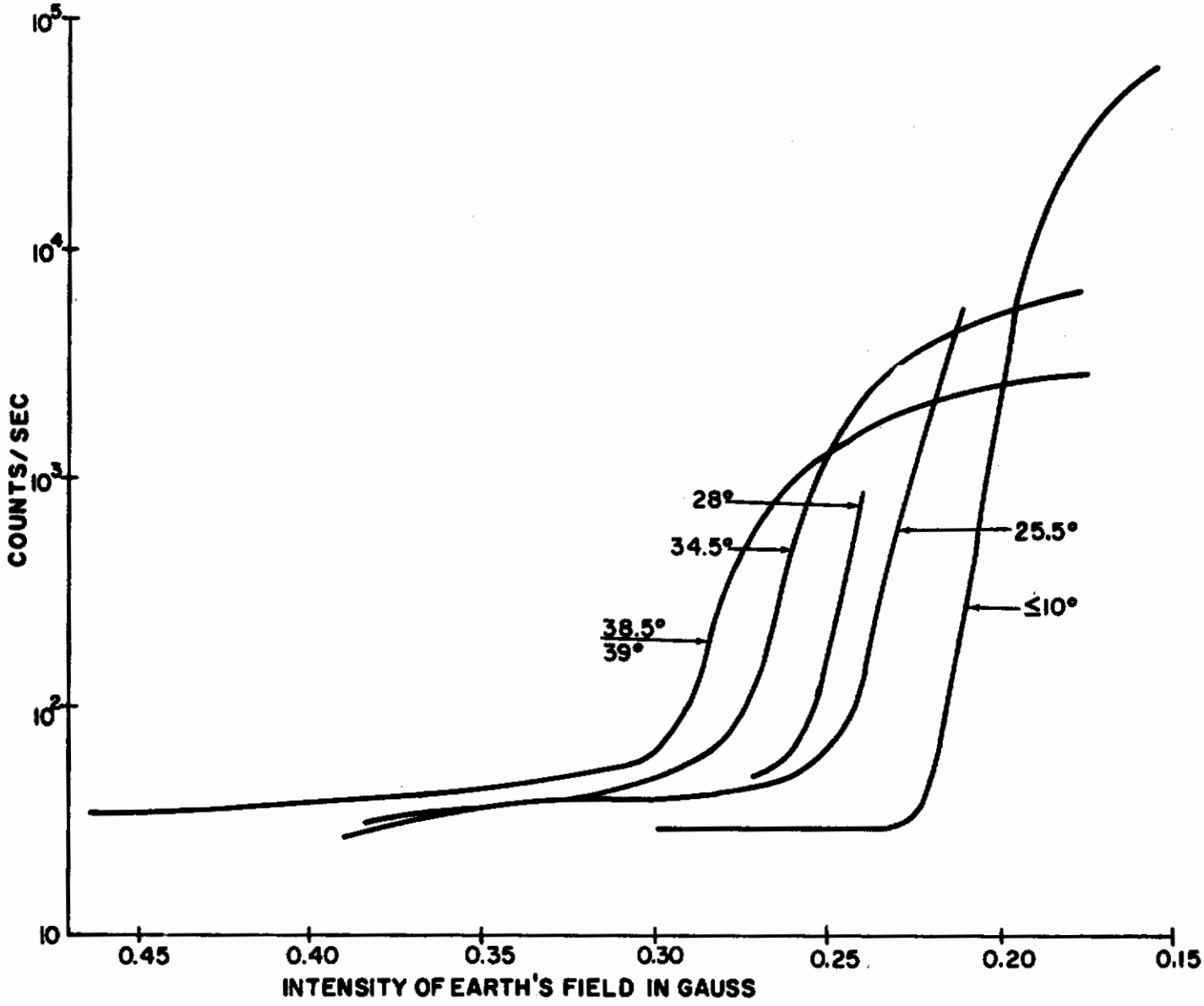

Figure 21. Variation of radiation intensity with geomagnetic latitude.[26]

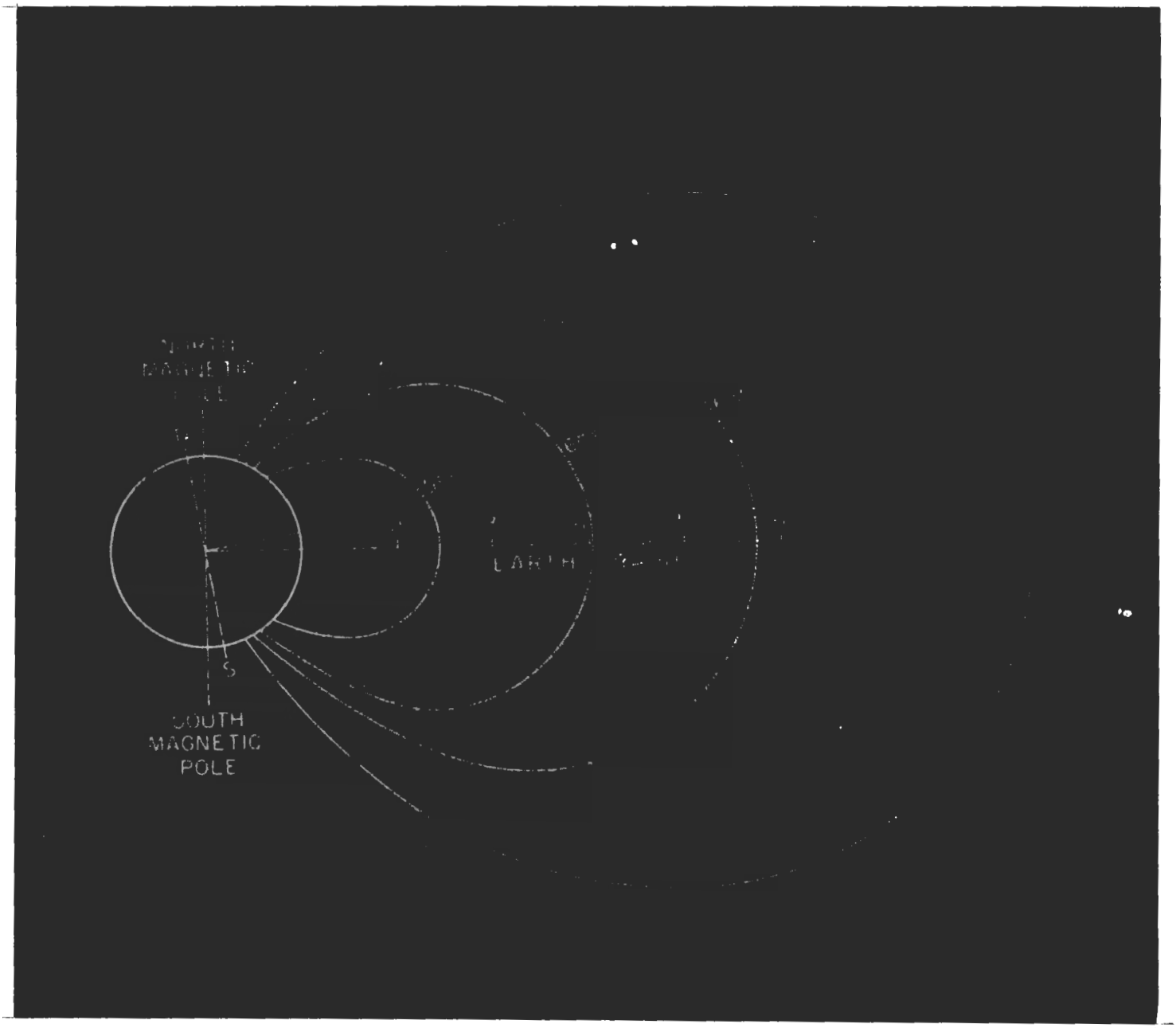

Figure 22. Pictorial conception of the trapped particulate radiation about the earth. The superimposed lines are a rough illustration of isomagnetic lines of force.

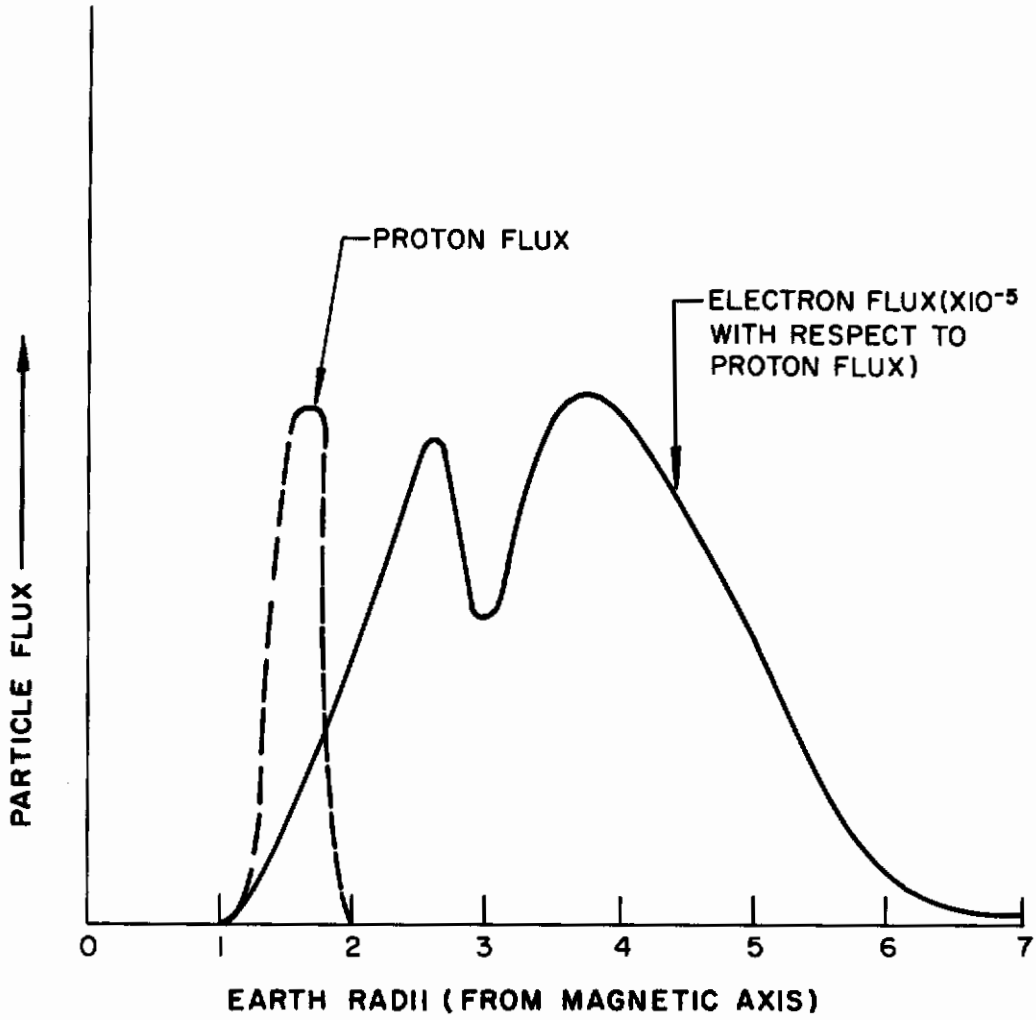

Figure 23. Theoretical representation of the particle flux about the earth.

straight line relation on a log-log plot of radiation intensity versus counts, the Geiger counter had a higher cutoff at the low end and a characteristic which dropped off at high rates. The Explorer VI observations recorded on Figure 23 were obtained during a period when the intensity was rising following a magnetic storm. Rapid changes in intensity have been encountered during such periods and the entire region is marked by extreme instability.

Representative of maximum values of radiation determined by the series of United States and Soviet measurements over the past three years, as modified by later observations, are the values shown in Table V.

TABLE V

Maximum Radiation Values

Inner Zone		
	Electrons	$E > 20$ kev, $\sim 2 \times 10^{10}$ electrons/cm^2 sec*
		$E > 600$ kev, $\sim 2 \times 10^{8}$ electrons/cm^2 sec*
	Protons	$E > 40$ Mev, 2×10^{4} protons/ cm^2 sec**
Outer Zone		
	Electrons	$E > 40$ kev, $\sim 10^{8}$ electrons/cm^2 sec***
	Protons	E (120 kev to 5 Mev), $\sim 10^{8}$ protons/cm^2 sec***
		$E > 10$ Mev, $< 10^{6}$ protons/cm^2 sec

* See reference 40.
** See reference 20.
*** See reference 38.

The results of observations at the edge of the inner zone obtained with an Atlas ICBM are shown in Figure 24.

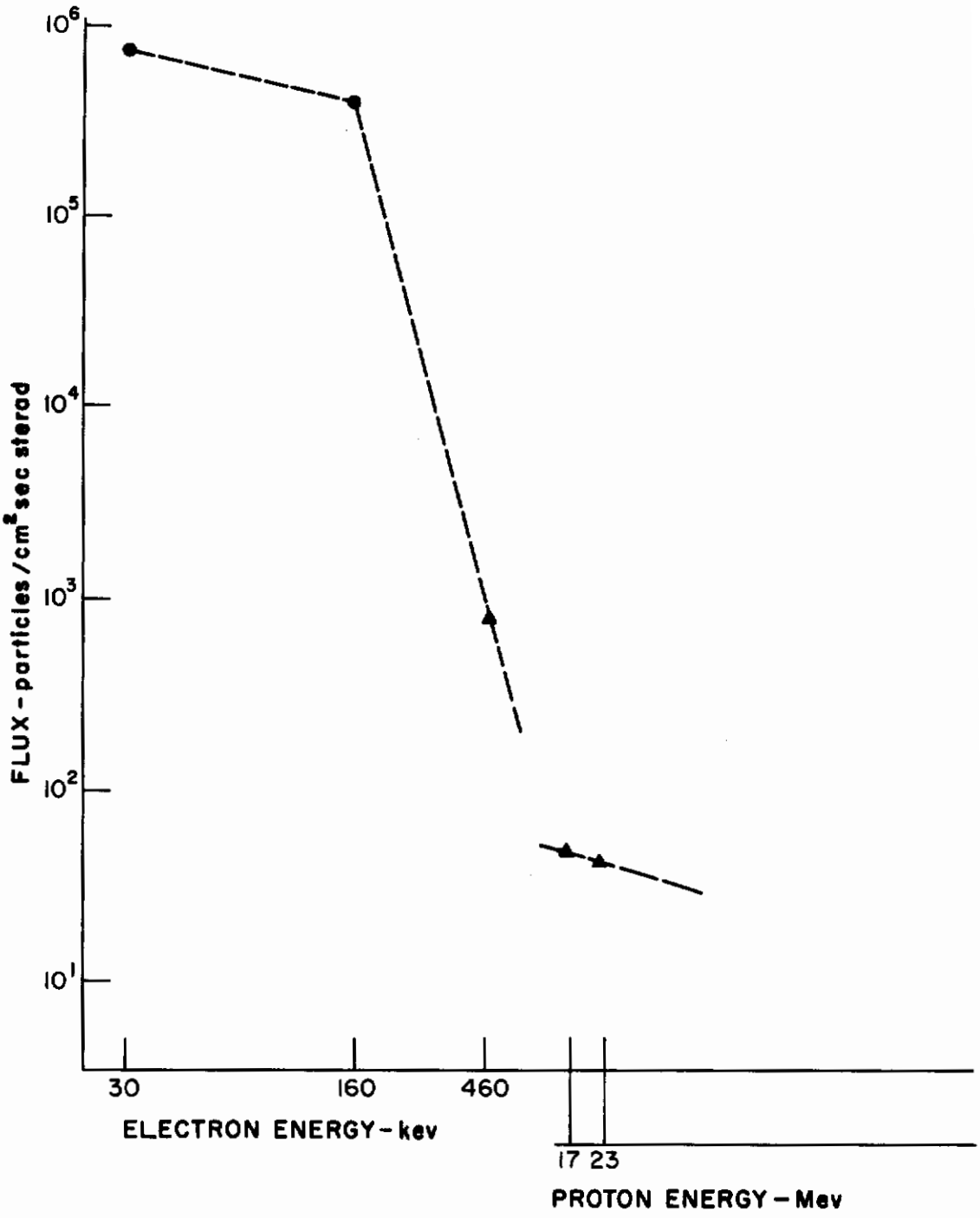

Figure 24. Energy levels of flux perpendicular to local magnetic field lines.[14]

The integral proton spectrum in the inner belt can be represented by the expression:[33]

$$N(>E) = K_i\, e^{-E/120} \text{ protons cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} ,$$

for proton energies between $40<E<750$ Mev. The value of K_i ranges between 0.2 and 1.7.[33] Based on this, the differential spectrum is then:

$$N(E)dE = K_d\, e^{-E/120}\, dE \text{ protons cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ Mev}^{-1} ,$$

where K_d ranges between 1.2 and 2.7. A depiction of the integral spectrum is shown in Figure 25.

The integral and differential electron spectrum in the inner zone has been found to be of the form:[33]

$$N(>E) = 1.2 \times 10^{9}\, e^{-E/.126} \text{ electrons cm}^{-2} \text{ sec}^{-1} \text{ (integral)} ,$$

and

$$N(E)dE = 9.3 \times 10^{9}\, e^{-E/.126} \text{ electrons cm}^{-2} \text{ sec}^{-1} \text{ kev}^{-1} \text{ (differential)} .$$

The electron spectrum for the inner zone can be shown as depicted in Figure 26. Though there is still major uncertainty regarding the electron flux in the outer belt, outer belt spectra have been found to match the following expressions on quiet days:[35]

$$N(>E) = 2.16 \times 10^{11}\, e^{-E/.026} \text{ electrons cm}^{-2} \text{ sec}^{-1} \text{ (integral)}$$

and

$$N(E)dE = 8.3 \times 10^{12}\, e^{-E/.026}\, dE \text{ electrons cm}^{-2} \text{ sec}^{-1} \text{ kev}^{-1} \text{ (differential)} .$$

The results of measurements by a rocket-borne magnetic spectrometer at relatively high latitudes are shown in Figure 27.[42] Above an energy of about 600 kev, the results are questionable because of scattering of low-energy electrons into the high-energy channels.

Maximum values of electron flux are in a direction perpendicular to the geomagnetic lines of force. The flux is not isotropic and it has been suggested that a cylinder open at both ends and oriented so that its axis is parallel to the lines of force would provide an effective shield. However, in many cases omnidirectional flux has been reported in technical literature because the orientation of the detector could not be determined.

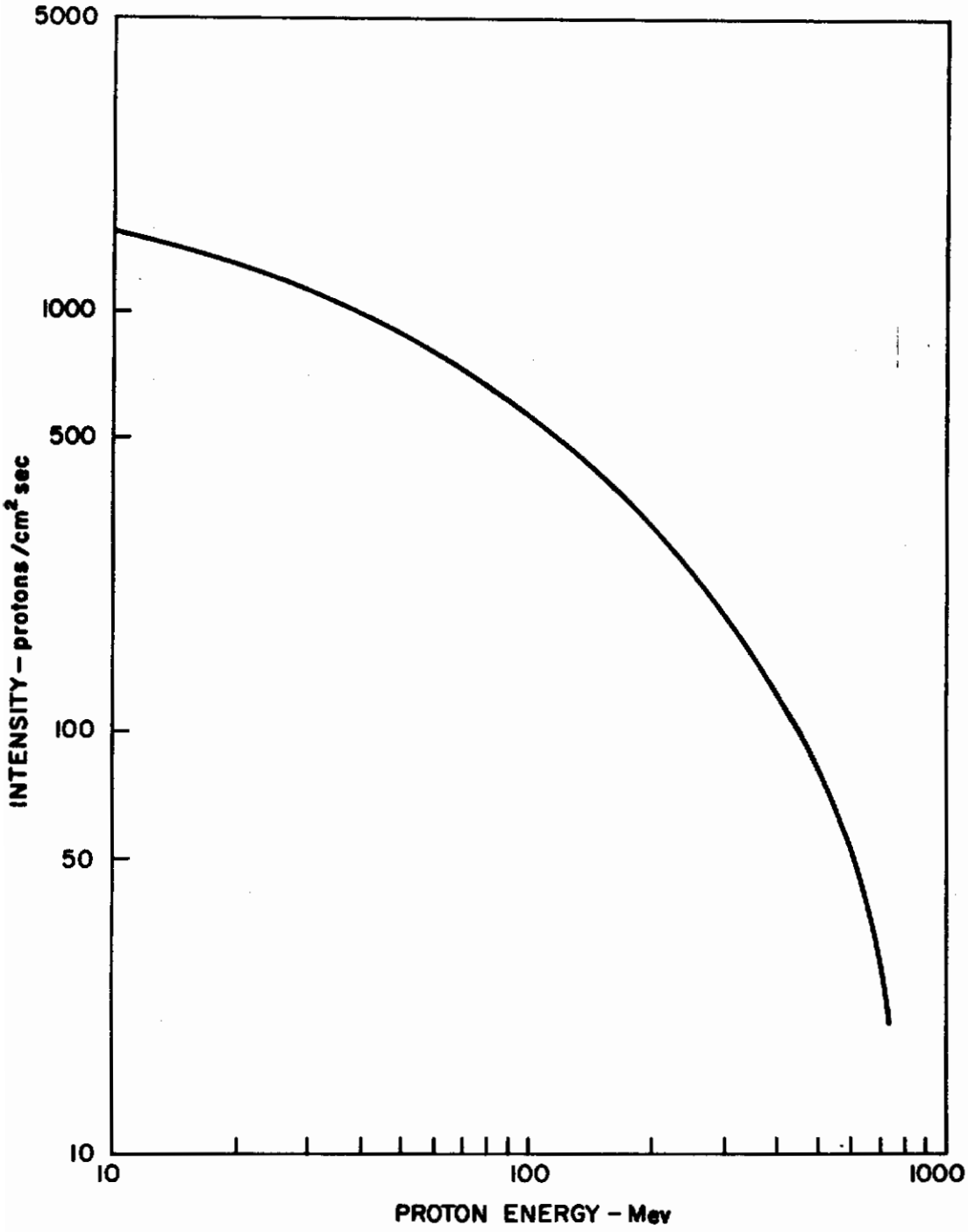

Figure 25. Integral proton energy spectrum in inner zone

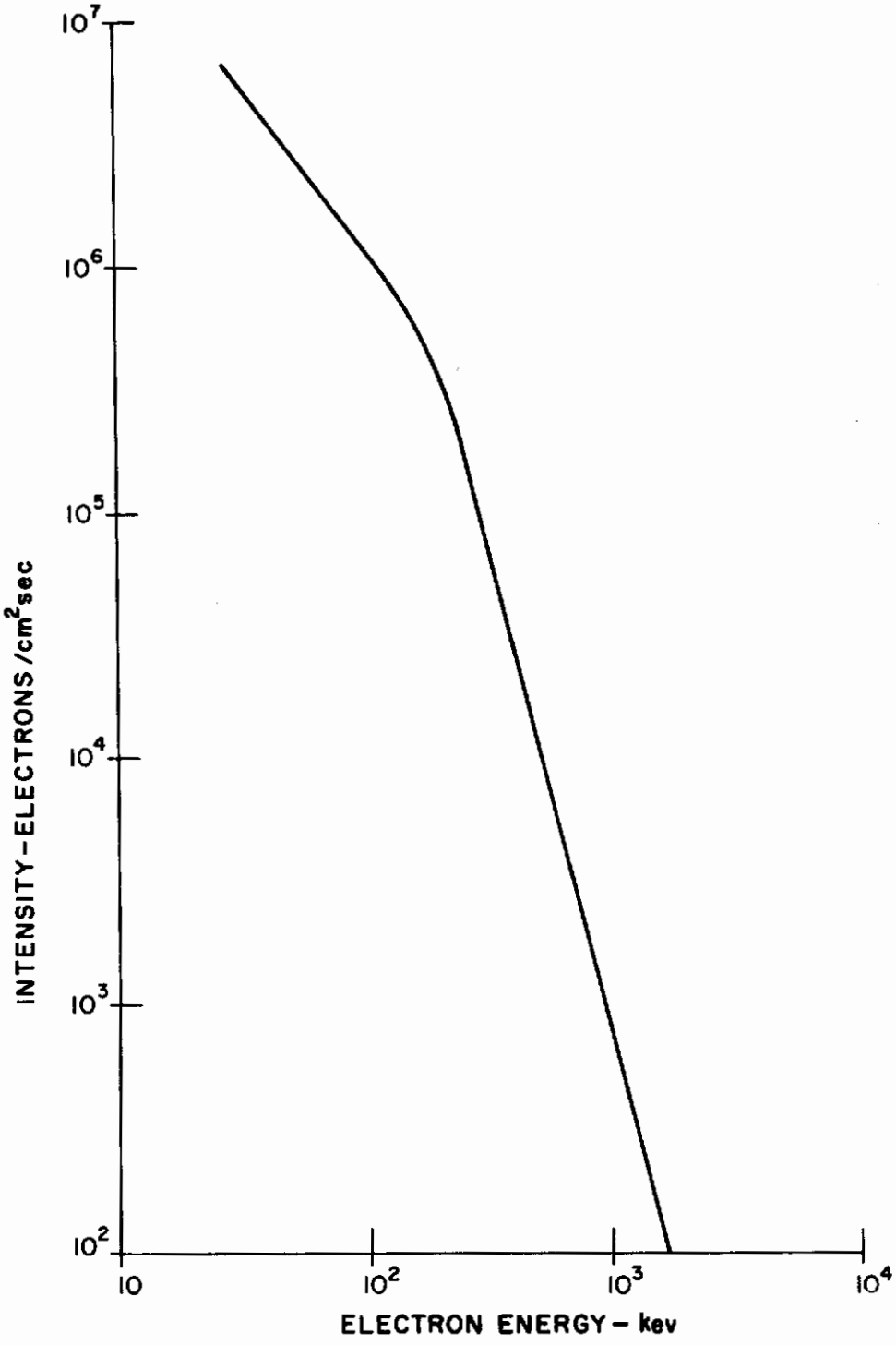

Figure 26. Integral electron energy spectrum--inner zone.

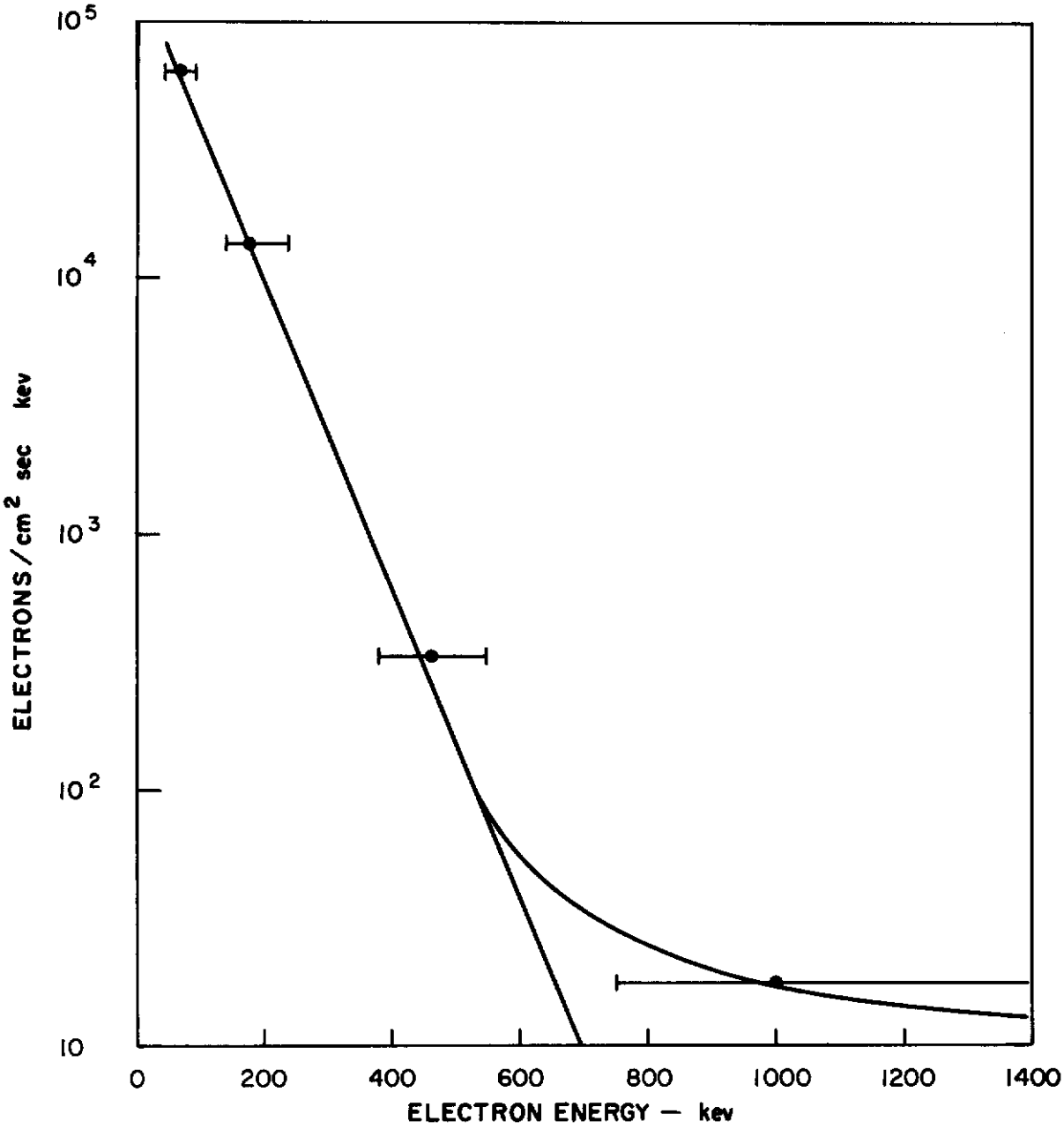

Figure 27. The electron differential energy spectrum measured between 600 and 1000 km.

At low latitudes, the intensity distribution of the radiation extends from an altitude of about 500 km out beyond 7 earth radii (43,000 km). Peak intensity of the protons in the inner zone, the P1 peak, is found at an altitude of about 3000 kilometers at the geomagnetic equator whereas the peak intensity or peak intensities, the E2 and E3 peaks, of the electrons in the outer zone are in a region 2 to 3 earth radii (13,000 to 19,000 km) from the earth's surface. In considering these limits, it should be realized that measurements to date have been at specific energy levels dictated by the characteristics of the detectors. Investigations over other ranges may show variation in peak intensities. The lower energy particles, in particular, have not been given close scrutiny and it was only recently[41] that an intense proton flux in the energy range of 0.5 kev to 1 Mev was reported in the inner zone. In the conference described in reference 38, it was noted that there is also a large population of low-energy protons (120 kev to 5 Mev) in the outer zone. The energy density of these protons is larger than that of any other component of trapped radiation measured to date.

The peak values given for the outer zone occur during periods of solar disturbance. As explained previously, the effect of solar disturbances and the resultant magnetic storms is still in controversy. Readings have indicated that there is an increase in protons above the 2 Mev level during or just after a geomagnetic storm as well as an increase in intensity and energy of electrons.

The results obtained from instrumentation aboard the Explorer XII satellite indicated that the intensity of low-energy electrons remains relatively constant until the region comes to an abrupt end at from 8 to 12 earth radii from the earth's center. The nature of this boundary has not been determined but it appears that outside the limits of the geomagnetic field a turbulent region exists in which a plasma or solar wind moves at high speed. The limit of 8 to 12 earth radii is for the sunlit side of the earth; on the side away from the sun the boundary of the geomagnetic field and the Van Allen belt may extend out to 20 earth radii.[39]

With regard to the inner boundary, the trapped radiation is of negligible intensity below an altitude of about 500 kilometers, undoubtedly due to the relatively high atmospheric density here. The nonionized atmosphere insulates the earth from the highly conductive regions in the exosphere. Experimental measurement of the ion concentration in the upper atmosphere led to the formation of a model[43] evisioning a predominance of oxygen ions in the region 500 to 1200 km altitude, a strong helium ion constituent from 1200 km to 3400 km, with protons which were a minor constituent throughout the region becoming dominant above 3400 km.

As has been noted, the regions within these boundaries are not regular or even steady. It has been proposed that the major discontinuity in the outer radiation belt, the gap in high intensity radiation between the E2 and E3 peaks, is the result of the Cape Town anomaly in the geomagnetic field.[3] In the general area of Cape Town, Union of South Africa, the earth's magnetic field has a minimum value. Accordingly, in this region, the mirror points for the charged particles would be close in to the earth's atmosphere. Scattering and absorption of the charged particles, and more particularly of the highly energetic particles, would produce a substantial decrease in particle intensity.

The outer zone is also indicated as the region of the geomagnetic ring current around the earth. Because of the radial gradient of the field strength, the trajectory of the particles undergoes a drift in longitude. Positively charged particles drift in an opposite direction to that of negatively charged particles. The movement of the charged particles constitutes an electric current or ring current, moving from east to west about the earth. This has appeared to wax and wane as magnetic disturbances increase or decrease. This variation has made positive determination difficult and there is a degree of uncertainty regarding both the extent and location of a ring current.

BIOLOGICAL EFFECTS

Although considerable data has been secured about a number of aspects of the particulate radiation in the Van Allen belt, evaluation of the effects on an astronaut has lagged. The ionizing power of the particles is still to be firmly established. An estimate of the effects that may be produced are given by the data shown in Table VI, page 62.

The high energy protons of the inner zone will not be attenuated to any marked extent by the skin of a space vehicle or even by a thin shield. At 100 Mev, the range of a proton is about 10 gm/cm^2 of aluminum and at 700 Mev this becomes 250 gm/cm^2. Thus, ordinary thicknesses of metal provide little protection against high energy protons. As indicated in Table VI, an estimate of an exposure level of about 20 roentgens/hour with a shield of 1 gm/cm^2 of steel has been made. There is one beneficial feature: A high energy proton passing through tissue may produce relatively few ion pairs per micron tissue compared to a lower-energy proton. In reference 28 it is noted that for protons there is probably no experiment that would really show an RBE value above 10. Protons above 50 Mev probably have an RBE of about 1 and for protons with an energy less than 50 Mev a safe value of the RBE was given as 5.

In reference 24 the relative biological effect of the Van Allen belt radiation is reviewed. Although the Code of Federal Regulations

TABLE VI

Radiation Belt Dose Rates

Inner Zone

Protons (No Shield)	E > 1 Mev ~ 55 r/hr, 70 rads/hr, 30 rems/hr*
	E > 40 Mev ~ 20 r/hr**
Electrons (No Shield)	E > 20 kev ~ 10^6 r/hr, 3 rems/hr***
	E > 600 kev ~ 10^3 r/hr‡
Protons (With Shield)	1 gm/cm^2 ~ 20 r/hr‡‡
	3.5 mm Pb ~ 3 r/hr**
	40 mils steel ~ 25 rads/hr‡‡‡
Electrons (With Shield)	The electrons, because of their relative low energy, cannot penetrate 40 mil steel, but their produced bremsstrahlung radiation can yield a dose rate through 40 mil steel ~ 2.1 rads/hr‡‡‡

Outer Zone

Protons (No Shield)	E > 60 Mev ~ 0.1 r/hr‡
Electrons (No Shield)	E > 20 kev ~ 10^8 r/hr, 300 rems/hr***
	E > 200 kev ~ 2×10^4 r/hr‡
Electrons (With Shield)	1 gm/cm^2 ~ 30-50 r/hr‡‡
	3.5 mm Pb ~ 0.05-0.1 r/hr‡‡
	Outer bremsstrahlung through 40 mil steel ~ 11.5 rads/hr‡‡‡

* See references 33, 34, and 35.
** See reference 3.
*** See references 30 and 34.
‡ See reference 30.
‡‡ See reference 23.
‡‡ See reference 31.
‡‡‡ See reference 35.

implies an RBE of 10 for high energy protons, it is pointed out that this applies to the radiation about atomic reactors in the region of 100 Mev and greater and with a peaked spectrum quite unlike that of the broad spectrum of energetic protons in the Van Allen belt. Based on a comparison of both the energy levels and the distributions, it is concluded that an RBE of 1 could be assumed where initial prefiltration of the radiation, when absorption will change the spectrum, is obtained from the skin of the vehicle and any other shielding.

The electrons in the outer zone present a different problem. With the bulk of the particle flux in the energy range of a few hundred kev range, it can be expected that a very thin layer of aluminum will prevent penetration into a space vehicle. The largest part of the exposure within the ship will be produced by x-rays from local bremsstrahlung. It has been suggested that a composite shield made up of a thin skin of light metal to stop the electrons and a sufficient thickness of lead to absorb the x-rays would provide reasonable protection in the outer zone. With this type of protection, it is estimated that the radiation dose produced by the outer zone electrons can be reduced to from 10 to 100 mr/24 hour day.

SECTION III

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SECTION IV

GALACTIC COSMIC RADIATION

HISTORY

The year 1961 is the "golden" anniversary of the discovery of cosmic rays. Back in 1911, not long after the discovery of radioactivity, Hess became curious to know why a well insulated electroscope would lose its charge. In those days it was generally believed that this loss was due to very weak radioactive decay radiation coming from the earth. Hess put this explanation to the test by carrying an ionization chamber away from the earth in a balloon. He observed that instead of the ionization decreasing as expected, it increased by a factor of five or ten at the maximum altitude of the balloon, and, in addition, regardless of where the experiments were carried out, over land or water, the same results were observed. Hess suggested that these rays were not only of a cosmic origin but were isotropically distributed. He referred to these rays as "hohenstrahlung". The war in Europe interrupted the cosmic ray study, but in 1922 the investigation resumed with further balloon flights. All experiments indicated that this radiation was of an extraterrestrial origin. Millikan called them "cosmic rays", a name now universally adopted.*

Our ideas as to the nature of cosmic rays have been revised radically and recurrently during the past few decades. Initially, it was thought that the primary cosmic rays were simply extraterrestrial electromagnetic waves or gamma rays. However, with the discovery of the geomagnetic latitude effect by Clay in 1928, it was established that these primary rays, or at least a large portion of them, consisted of charged particles, thought to be electrons at that time. The discovery of a west-to-east excess (east-west assymmetry) in the cosmic radiation by T. H. Johnson in 1938 indicated the existence of many more positive rays than negative. A series of high-altitude balloon experiments by Schein, et al., in 1941 revealed that the charged particles were protons and not electrons or positrons. Extension of these measurements with rockets above the atmosphere (above 45 km) assured that the charged particles were protons. In 1948 further discoveries were made with the introduction of photographic plates and cloud chambers which indicated the existence of not only protons but primary heavier nuclei from those of helium to nuclei of iron.[65, 66]

* See reference nos. 4, 22, and 71.

During the past decade this galactic cosmic ray picture has changed little in a qualitative way, although many balloon, rocket, and satellite measurements have gained much quantitative information concerning the absolute intensities, energy spectra, relative abundance, and chemical composition of the various components of the primary galactic radiation.

The reasons for studying cosmic ray physics are to gain some insight toward answers related to the following questions: What are cosmic rays? Where do they originate? How are they produced? How do they achieve their prodigious velocities? Does their presence in distant parts of the universe give rise to observable effects on the earth? What happens when extremely energetic particles (cosmic rays) collide with atoms and nuclei? Does cosmic radiation produce detectable changes in the isotopic composition of the earth? What relation, if any, exists between cosmic rays and the evolution of life?

In addition, one would like to study the strange particles produced as a result of cosmic-ray interactions in order to shed new light on the atomic and nuclear structures;[22] to gain knowledge of the properties of the space in which these rays travel before reaching the earth as well as to learn more of our universe;[71] to determine quantitatively the charge spectrum of the primaries and the relations of the elemental abundance of outer space to that on earth;[66] to discover the shape of the energy spectra and absolute intensity of the various components of the galactic radiation as well as the time variations and their mechanisms;[65] and to assess the human biological hazards associated with galactic radiation with regard to manned space travel.

It is possible today to answer some of these questions, at least partially, from the presently available information with a certain degree of confidence. Briefly, cosmic rays are predominantly primary nuclei of various elements including a very small electron component, which move with great velocity in the stellar conglomerations of our galaxy and probably other galaxies as well. Their origin is believed to be connected with explosions in the interior or on the surface of stars or perhaps supernovae. They receive their energy probably by interacting with magnetic fields imbedded in the ionized gas clouds which are expelled during such explosions. Their presence in distant regions of space can be detected by the emission of polarized light and radio waves. When they collide with nuclei and atoms, they produce a great variety of reactions and new particles. They have been incident on the earth for millions of years and have produced detectable changes in its isotopic composition. During the history of the earth there were probably periods of increased cosmic ray

intensity resulting in increased mutation rates which could be responsible for far-reaching evolutionary changes.[55] As far as they go, the answers to these questions are probably correct, but new questions and greater progress toward understanding are being compiled every day. It is the aim of this report to give a brief account of this understanding that is available to date.

ORIGIN OF THE GALACTIC COSMIC RADIATION

The question of the origin of these galactic cosmic radiations arose, naturally, immediately after its discovery, but for a long time only purely hypothetical discussions were possible since very little was known about this primary radiation. Recently after the composition of the primary radiation in the neighborhood of the earth was evaluated to a first approximation between 1948 and 1953, conclusions about the distribution of cosmic radiation in the galaxy and beyond its boundaries were enhanced by radio-astronomy data.[21]

There are, at the present time, two major competing theories on the origin of the galactic cosmic radiation. According to one theory, the cosmic particles are emitted by certain localized objects in our galaxy, such as supernovae and novae. It has been discovered that there exists within the galaxy a series of intense radio-nebulae (discreet sources of cosmic radio emissions). The emission from these objects is of a bremsstrahlung character. It follows then that there is a high concentration of cosmic electrons in these radio-nebulae, which represent the envelopes of supernovae, and therefore it is plausible that high intensities of energetic cosmic protons and other heavier nuclei are also present.

Nearly all of the existing information available today leads to this hypothesis that galactic cosmic radiation originates in the expanding envelopes of supernovae and also possibly novae within the galaxy. Coming out into the interstellar media, with their full energies, from the envelopes of the stars which lie in the region of the galactic plane, cosmic particles fill the whole quasi-spherical galaxy, and there they eventually lose their energy, mainly as a result of nuclear collisions. According to one theory, acceleration of these cosmic particles to their final energies occurs within the envelopes of supernovae. The low energy portion of this radiation, in theory, should be isotropically distributed as a result of scattering in the expanding envelope. The high energy particles, however, will be preferentially directed, i.e., particles of energies $>10^{16}$ ev originating from these localized sources should have an uneven distribution.*

* See reference nos. 40, 55, and 59.

According to the second theory, originally proposed by the late Enrico Fermi, the galactic cosmic-ray particles are emitted at low energies, presumably by stars like the sun. These particles are then gradually accelerated as they wander around the galaxy. The general accelerating mechanism is as follows. Magnetic fields in interstellar space are known to be associated with moving clouds of ionized gases, associated with the spiral arms of the Milky Way. As these clouds travel about, they carry with them magnetic lines of force. It is the interactions of the cosmic particles with these moving lines of force that accelerate the galactic cosmic rays. These magnetic fields trap the particles in the galaxy for millions of years, allowing the slow acceleration process to build up the particle energies to the observed values. At each encounter with a magnetic field, a charged primary would receive a tiny boost in energy. Through a large number of such encounters, these galactic primaries would eventually acquire the high energies of the observed primaries. As the energy of the trapped particles increases, the trajectories of the particles would become less and less curved. When the radius of the curvature becomes comparable to the thickness of the galaxy, the particles would escape into intergalactic space. The radius of our galaxy is on the order of 3.1×10^{22} centimeters, and the energy of escape lies between 10^{17} and 10^{18} ev. Therefore, the galactic cosmic ray particles that enter the earth's atmosphere will be isotropically distributed and the number of incoming particles should abruptly drop to zero at energies slightly above the critical cutoff energy of $\approx 10^{18}$ ev.*

In summary, either theory on the origin of the galactic cosmic radiation (the acceleration of cosmic particles as a result of supernovae outbursts or the Fermi accelerator theory) is, within the limits of our present information, independently acceptable, and sufficient for the explanation of all known facts about the galactic radiation. It remains for future experiments to establish which phenomenon predominates or whether both contribute equally or if there exists yet another source of this galactic radiation.

PROPERTIES--PRIMARY COSMIC RADIATION

The energetic particles to be found in space outside the earth's environment are in general divided into two main categories. The first category consists of that cosmic radiation which penetrates to the solar system from without, and will be designated here as Galactic Cosmic Radiation. Whether this radiation originates in the galaxy or outside it is a question which has not been settled at the present time. This radiation

* See reference nos. 3, 16, 21, 40, 47, and 59.

is of very high energy and is known to have a solar controlled intensity modulation associated with it. The second category is that radiation which originates from the sun, and will be designated here as Solar Radiation. This radiation is emitted from the vicinity of the sun at the time of a large solar flare. The peak intensity of this radiation near the earth's orbit is many times higher than that of the galactic cosmic ray background but is of lower energy, usually consisting of particles having nonrelativistic velocities. Solar corpuscular radiation was covered in a separate section of this guide (Section II) along with a description of the solar electromagnetic radiation.

The Galactic Cosmic Radiation

The galactic cosmic rays are extremely high-energy electrically charged particles that continually bombard the earth from all directions. With energies in the range 10^8 to 10^{19} ev, these galactic cosmic rays consist of nucleons or atomic nuclei which have had their orbital electrons stripped away.

Of the incident primary nucleons approaching the earth, approximately 75 to 80 percent consist of protons, about 15 to 19 percent are alpha-particles, and the remaining 1 to 3 percent are nuclei of higher atomic numbers.[46] Table VII shows the elemental abundance of the primary heavier nuclei.[81] So far as can be determined, there are very few primary electrons and gamma rays present in the primary galactic radiation. Measurements indicate that the intensity of primary electrons is about $5 \pm 4 \times 10^{-3}$ particles cm^{-2} sec^{-1} $ster^{-1}$, with a primary gamma ray flux of about 1 ± 3 photons cm^{-2} sec^{-1} $ster^{-1}$. Primary neutrons are not present in the radiation as would be expected because of their extremely short half-life.*

Within the limits of accuracy, the particle flux as a function of atomic number follows the chemical abundance of the elements of the universe. Table VIII gives numbers which convey some idea of the distribution of the various atomic species.* The relative abundance of the various chemical elements in the galactic cosmic radiation are compared to the universal abundance, as measured by astronomical techniques, in Table VIII. The numbers listed pertain to all nuclei regardless of energy. Within the rather wide bounds of experimental error, one can say that the comparisons in Table VIII indicate that the galactic cosmic radiation is an average sample of the elements in the universe which have been accelerated to very high velocities.

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* See reference nos. 7, 8, 11, 12, 45, and 46.

* See reference nos. 40, 46, 50, and 57.

TABLE VII

Abundance of Elements in the Heavy Primary Cosmic Radiation

Element	Atomic Number, z	Abundance, %
Ne	10	23.1
Na	11	14.7
Mg	12	16.3
Al	13	11.5
Si	14	7.2
P	15	5.1
S	16	2.5
Cl	17	2.6
A	18	2.0
K	19	2.5
Ca	20	1.8
Sc	21	2.0
Ti	22	2.0
V	23	1.4
Cr	24	1.7
Mn	25	0.6
Fe	26	1.3

TABLE VIII

Galactic Cosmic Ray Abundance
Compared to the Universal Abundance

(Units in Atoms/10^6 Hydrogen Nuclei)

Element Group	Relative Abundance in Cosmic Rays	Universal Abundance
Hydrogen	100,000	100,000
Helium	10,000-15,000	7,700-10,000
Light Nuclei (Li, Be, B)	100-240	~0.1
Medium Nuclei (C, N, O, F)	500-1200	~300
Heavy Nuclei ($10 \leq Z \leq 30$)	200	~100
Very Heavy Nuclei ($Z \geq 31$)	$<10^{-4}$	$\sim 10^{-6}$
Electrons and Gamma-Rays with E > 4 Bev	1000	----

The data listed in Table VIII for He, C, N, O, F, and $Z \geq 10$ are correct to about 25 percent. The remaining abundances, as well as the data on universal abundance, are probably correct within a factor of 1.5. The latter are compiled mostly from the analysis of steller spectra and from the chemical composition of the earth's crust and of meteorites.

PRIMARY ENERGY SPECTRUM

The energy spectrum of cosmic radiation is another subject that has been quite extensively investigated. The energy range that has

been most studied is from less than one Bev to around 15 Bev. This is the range in which the earth's magnetic dipole field acts as a magnetic spectrometer. Up to 10^{12}-10^{13} ev, the protons have been separated from the heavier elements; above this energy no distinction can be made between different particles, primarily due to the fact that the fluxes are too low to obtain adequate data. In the region where separated, the primaries show an integral spectrum similar to that of protons when represented as energy per nucleon; see Figure 28.

The primary nuclei belonging to different elements have essentially identical energy spectra. In the energy range of $0.5 < E \leq 1000$ Bev/nucleon, the number of incident particles of atomic number Z passing through a one-square-meter area each second from directions lying within a steradian or unit solid angle (a unit designated as a peter) with kinetic energy per nucleon in excess of E(Bev/nucleon) can be represented by a power law function of the form:

$$N_Z (>E) = k_Z (1 + E)^{-1.4 \pm 0.3} \text{ peters} ,$$

where

$$\begin{aligned} k_{(\text{protons})} &= 4500 \pm 500 \\ k_{(\alpha\text{-particles})} &= 370 \pm 70 \\ k_{(3 \leq Z \leq 5)} &= 13 \pm 3 \\ k_{(6 \leq Z \leq 9)} &= 27 \pm 7 \\ k_{(Z \geq 10)} &= 10.9 \pm 5. \end{aligned}$$

The exponent of the spectrum increases as the energy increases up to 10^{16} ev, and approaches a value of 1.8,* indicating that the exponent is not strictly energy independent.

Figure 29 shows the integral-energy spectrum for protons and the total component for $E > 10^8$ ev; the techniques by which the experimental points were obtained are indicated. From the figure it can be seen that the spectrum becomes gradually steeper going toward higher energies; in the region between $10^{10} < E < 10^{18}$ ev, it can be represented by a power law

$$N(>E) = 10^{13} E^{-(0.67 + 0.037 \log E)} \text{ peters} ,$$

where E is in ev. The spectrum in the region of 10^{18} ev and above is of

* See reference nos. 17, 29, 39, 40, 42, 46, 50, 52, 66, 77, and 78.

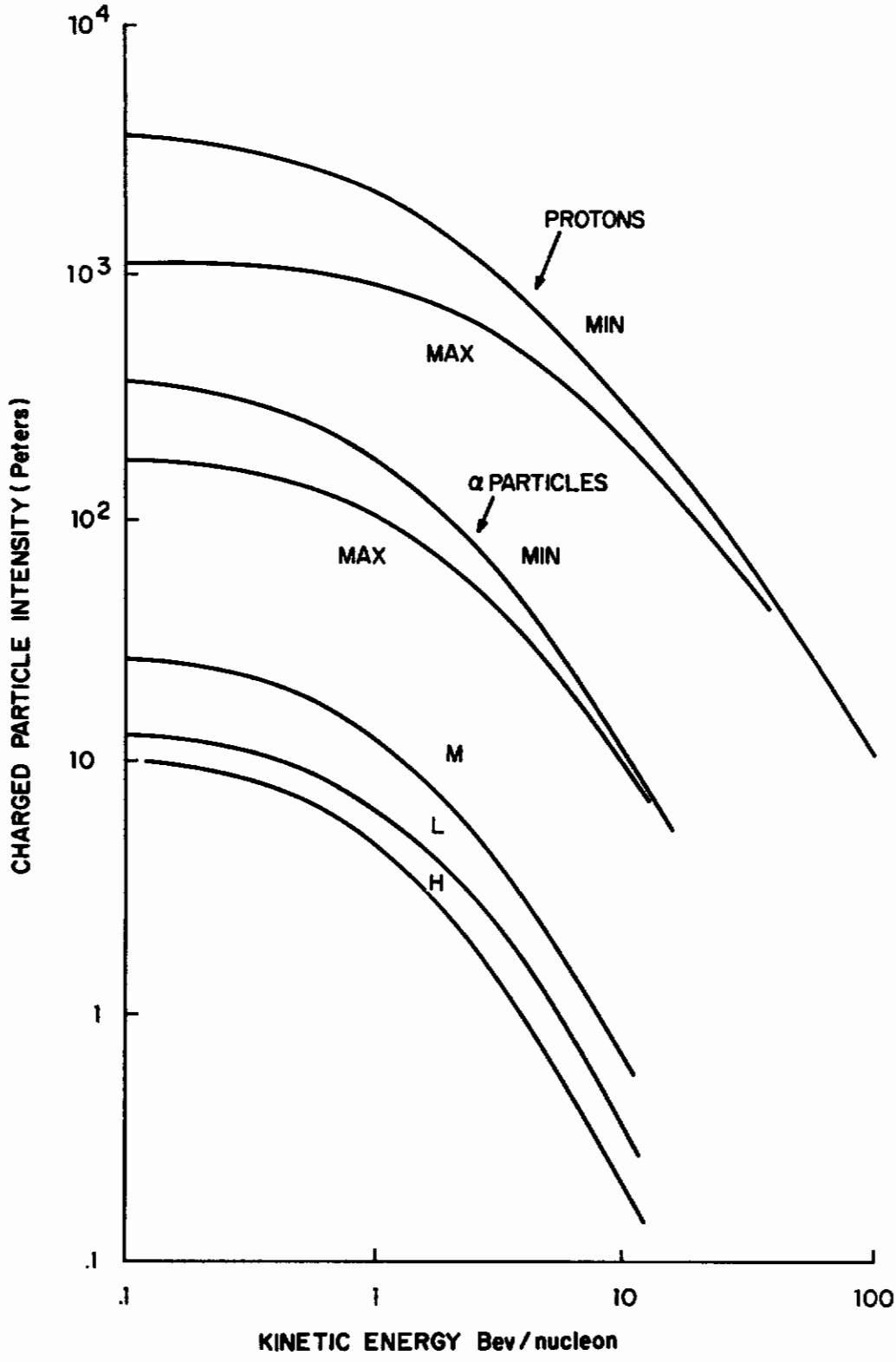

Figure 28. The integral energy spectra of the various primary particle components of the galactic cosmic radiation.

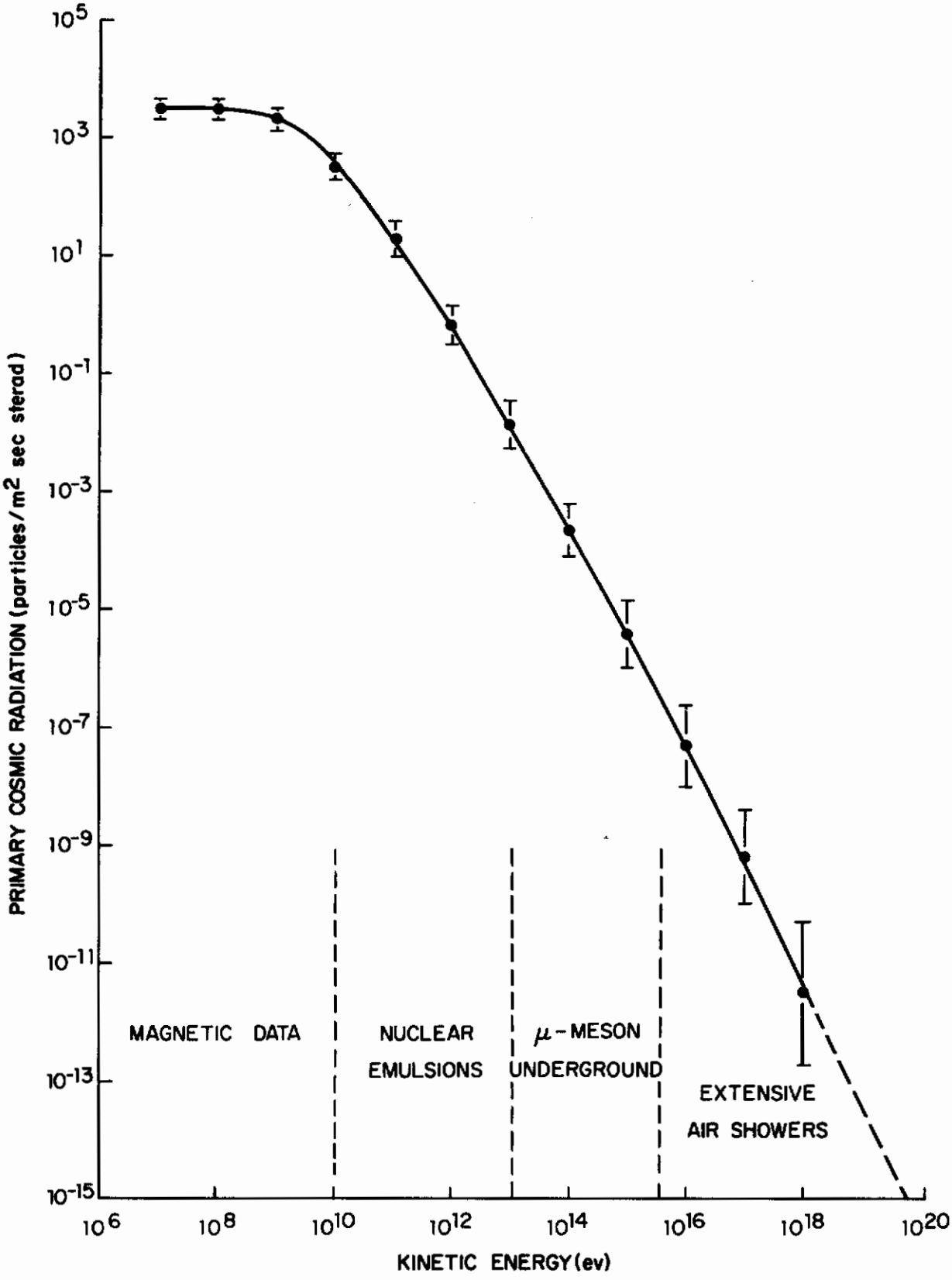

Figure 29. Integral energy spectrum of the total primary component of the galactic cosmic radiation.

crucial importance to the problems of origin and mechanism of acceleration of the primary radiation. Data in this region are not available today, largely because of the extremely low frequency of observation of the events.

The differential spectrum of cosmic radiation is defined as the number of primary nuclei of energy between E and E + dE per unit area, per unit time, per unit solid angle, and should not be confused with the integral spectrum or flux which is defined as the flux of particles with energy exceeding E. The differential spectra is represented by a power law of the form

$$N(E)dE = k_z (1 + E)^{-2.4 \pm 0.3} dE ,$$

where

$$k_{(\text{protons})} = 6300 \pm 500$$
$$k_{(\alpha\text{-particles})} = 520 \pm 70$$
$$k_{(3 \leq Z \leq 5)} = 18 \pm 3$$
$$k_{(6 \leq Z \leq 9)} = 38 \pm 7$$
$$k_{(Z \geq 10)} = 15 \pm 5.$$

Figures 30 and 31* show the differential energy spectra for alpha-particles and protons. The spectra for the heavier nuclei are essentially the same as that for alpha-particles and protons at solar minimum. The average energy of the incident primary cosmic radiation is about 3.5×10^9 ev/nucleon, and the energy flux through a solid angle of 2π steradians falling on the surface of the earth near the poles, almost unaffected by the earth's magnetic field, is about 7×10^{-3} ergs/cm^2/sec. The energy density of cosmic radiation near the earth is about 0.6 ev/cm^3, which is about equal to that of starlight. On the average, a total of 5.7×10^{17} cosmic rays arrive over the entire earth every second, corresponding to a total current influx of about 0.09 amperes. The influx of energy is estimated to be 9.8×10^{18} Bev/sec, or about 1.4×10^9 watts.**

The study of the differential components of the galactic cosmic radiation has been accomplished by a variety of methods, with rockets and balloon-borne instrumentation and recently in satellites. The instruments primarily used in these studies have been photographic emulsion plates,

* See reference nos. 17, 39, 42, and 52.

** See reference nos. 57 and 66.

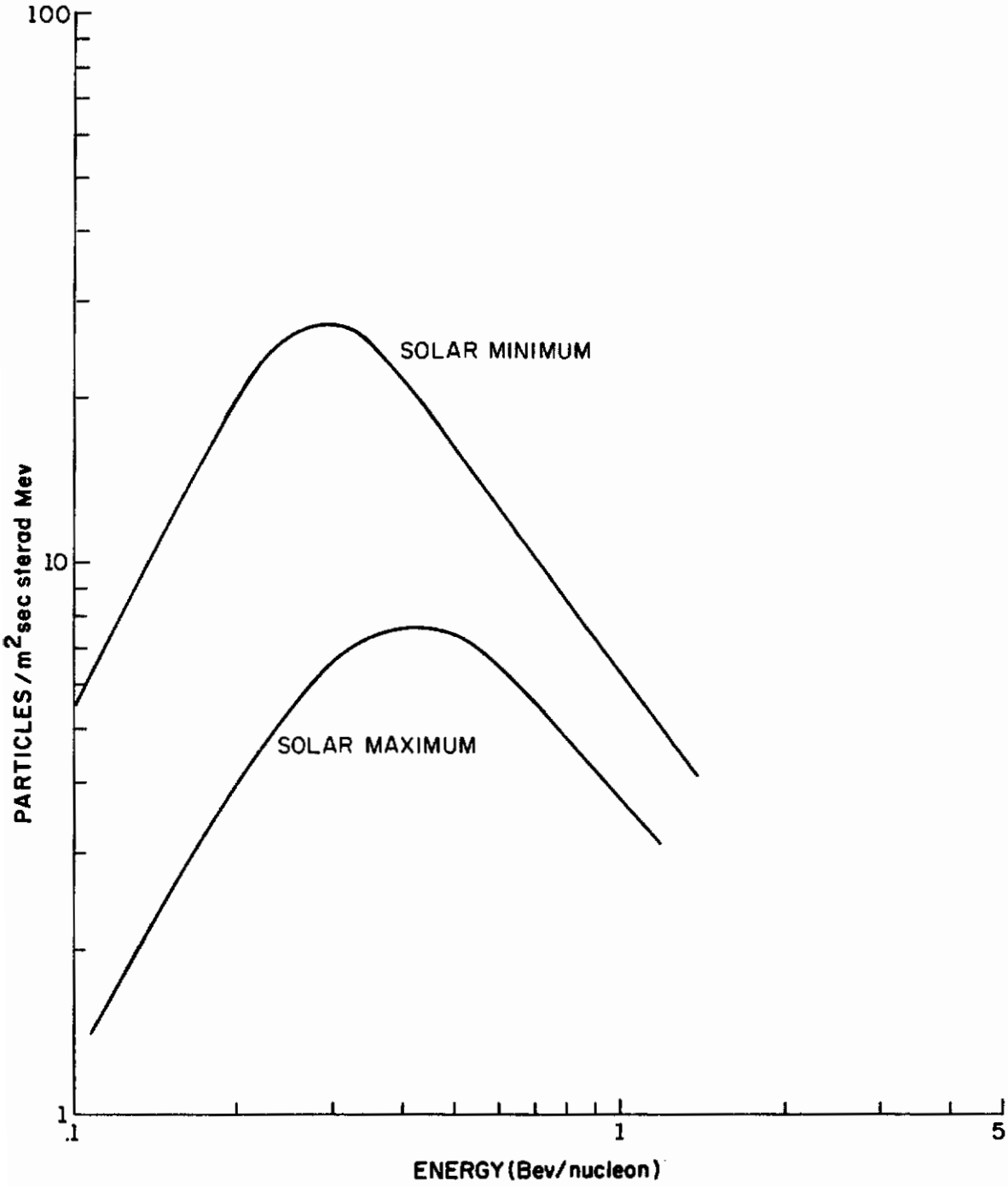

Figure 30. Differential energy spectra for primary protons or alpha particles at solar minimum or maximum. The alpha particle spectra are multiplied by 6.5.

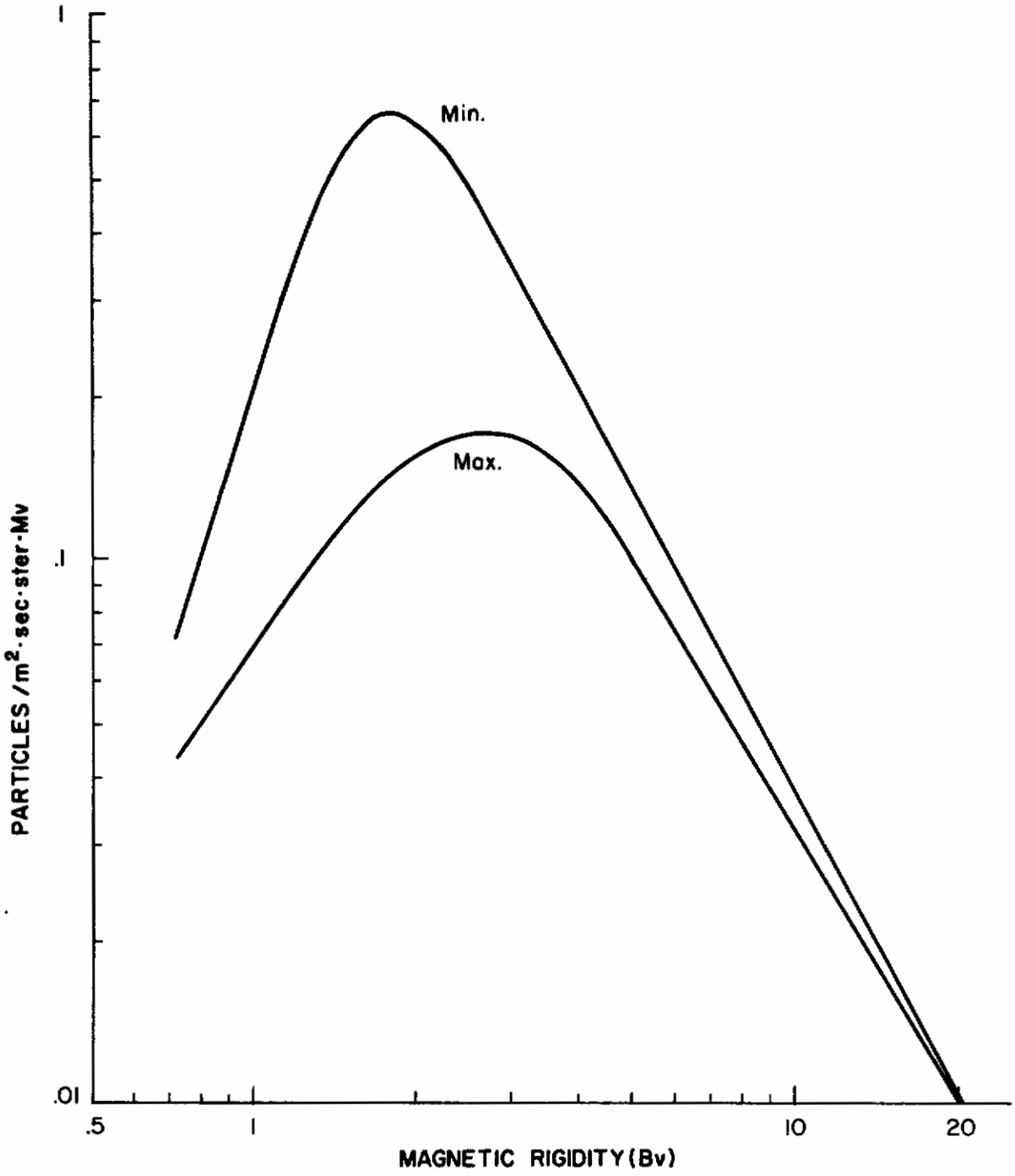

Figure 31. Differential rigidity spectra for primary protons or alpha particles at solar minimum or maximum. The alpha particle spectra are multiplied by 6.5.

cloud chambers, Cerenkov and scintillation counters, proportional counter telescopes, and omnidirectional ionization chambers.

THE PRIMARY PROTON GALACTIC INTENSITY

The quiescent primary proton intensity as a function of geomagmetic latitude changes slowly in some detail during the solar activity cycle (particularly the low energy end, i.e., for geomagnetic latitudes of $\lambda > 40^{o}$). It also undergoes more rapid changes during magnetic storms. However, these variations in intensity and spectrum will be discussed in detail in the section on Time Variation. Figure 32 shows the primary proton intensity as a function of geomagnetic latitude at the time of solar maximum and minimum. Also associated with this radiation are "albedo" protons or upward-moving low energy secondary protons which eventually become trapped in the earth's magnetic field contributing to the lower Van Allen radiation belt. Also included in this figure is the primary intensity as a function of geomagnetic latitude for alpha-particles, L nuclei ($3 \leq Z \leq 5$), M nuclei ($6 \leq Z \leq 9$) and H nuclei ($Z \geq 10$).*

Nuclei of elements Li, Be, B are practically absent in the universe's matter distribution, but present in appreciable amounts in the galactic cosmic radiation. The apparent absence in the universe can be explained by the fact that these elements undergo thermonuclear reactions at temperatures of about 10^{6} ^{o}K. Such temperatures are known to exist in the interiors of stars. The presence of these nuclei in the galactic cosmic radiation is probably due to the prolonged wandering of the primaries in interstellar space, and are derived from the fragmentation of the heavier nuclei.** The relative concentrations of groups of nuclei are given in Table IX.**

The calculated primary flux values at geomagnetic latitude $\lambda = 41^{o}$ for deuterons, tritons, and Helium-3 are about 32 peters for ^{2}H, one peter for ^{3}H, and 41 peters for ^{3}He.[52]

Measurements show that the galactic cosmic radiation is spatially isotropic near the earth. Recent space probe measurements place the free-space flux of particles at solar maximum at about 2.2 particles/cm^{2}/sec with an unshielded dose rate of about 0.6 mr/hr. At solar minimum the free-space flux is about twice that at solar maximum (or about 4 particles/cm^{2}/sec) with a dose rate of about 1.8 mr/hr.

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* See reference nos. 48, 50, 52, 66, and 74.

** See reference nos. 36 and 66.

** See reference nos. 41, 52, 66, and 80.

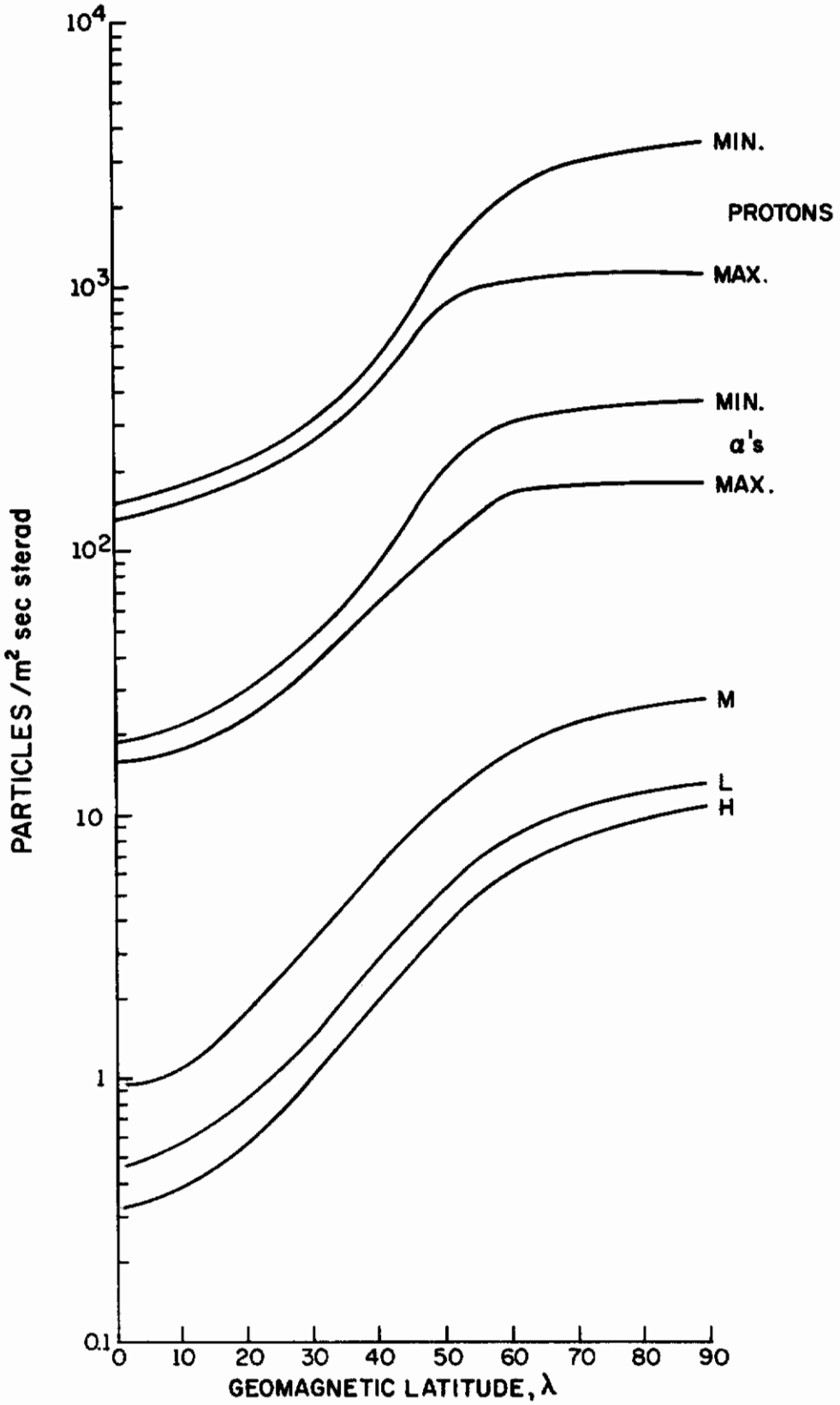

Figure 32. Intensity of the various primary components of the galactic cosmic radiation as a function of geomagnetic latitude.

TABLE IX

Relative Concentration of Groups of Primary Nuclei

$\frac{P}{\alpha} = 10$	$\frac{\alpha}{H} = 49$
$\frac{\alpha}{M} = 18$	$\frac{L}{H} = 1.2$
$\frac{L}{M} = 0.45$	$\frac{P}{H} = 486$
$\frac{H}{M} = 0.37$	$\frac{M}{VH} = 10.3$
$\frac{M}{H} = 2.7$	$\frac{VH}{H} = 0.3$
$\frac{P}{M} = 180$	

where:

P = (protons)

α = (α-particles)

L = ($3 \leq Z \leq 5$)

M = ($6 \leq Z \leq 9$)

H = ($Z \geq 10$)

VH = ($Z \geq 20$)

Figures 33 and 34 show the cosmic ray dose rate as a function of geomagnetic latitude and altitude during the periods of minimum and maximum solar activity. The peaks in the curves of Figure 33, at between 55,000 and 75,000 feet, are due to the secondary cascade showers of mesons, nucleons, electrons, and photons which are created as a result of the interaction of high-energy cosmic primaries with the atmospheric constituents. The reason that no peak is observed at high latitudes during solar minimum (Figure 34) is due to the fact that there are more low energy particles present in the primary radiation during this period than were available during solar maximum, and these low energy particles produce relatively fewer secondaries than the more relativistic particles. The decrease in cosmic ray dose rate with decreasing magnetic latitude, as shown in Figure 35, results from the increased shielding offered by the earth's magnetic field against the relatively lower-energy cosmic particles. Figures 36 and 37 show that the increase is cosmic ray dose rate at increasingly great distances from the earth arises from a combination of two factors: (1) The decrease in the solid angle subtended by the earth; and (2) the decrease in geomagnetic field strength with a corresponding decrease in cosmic particle deflection.

The interplanetary galactic cosmic radiation varies with increasing distance from the sun as dictated by the interplanetary magnetic solar field. This field, which predominates throughout the entire solar system and decreases in strength from the sun out, contains magnetic scattering centers which can deflect charged particles and as a result produce a negative cosmic ray intensity gradient in the direction of the sun. Pioneer V has observed this field and has measured an intensity gradient on the order of magnitude of 20 percent per astronomical unit (the mean distance from earth to sun: 92.9×10^6 miles).*

THE TIME VARIATION OF THE GALACTIC COSMIC RAY INTENSITY

Increased observations during the IGY have made it clear that galactic cosmic ray intensity in free space is subjected to large variation. Two basic types of changes can be distinguished: (a) systematic long-term changes correlated to the eleven-year solar cycle; and (b) irregular short-term changes apparently correlated to the daily variation of solar activity. All of these complex changes have one trait in common. They pertain exclusively to the low energy part of the spectrum. Biologically, the most effective part of the total primary cosmic ray beam is the low

* See reference nos. 24, 33, 38, 48, 49, 50, 58, and 70.

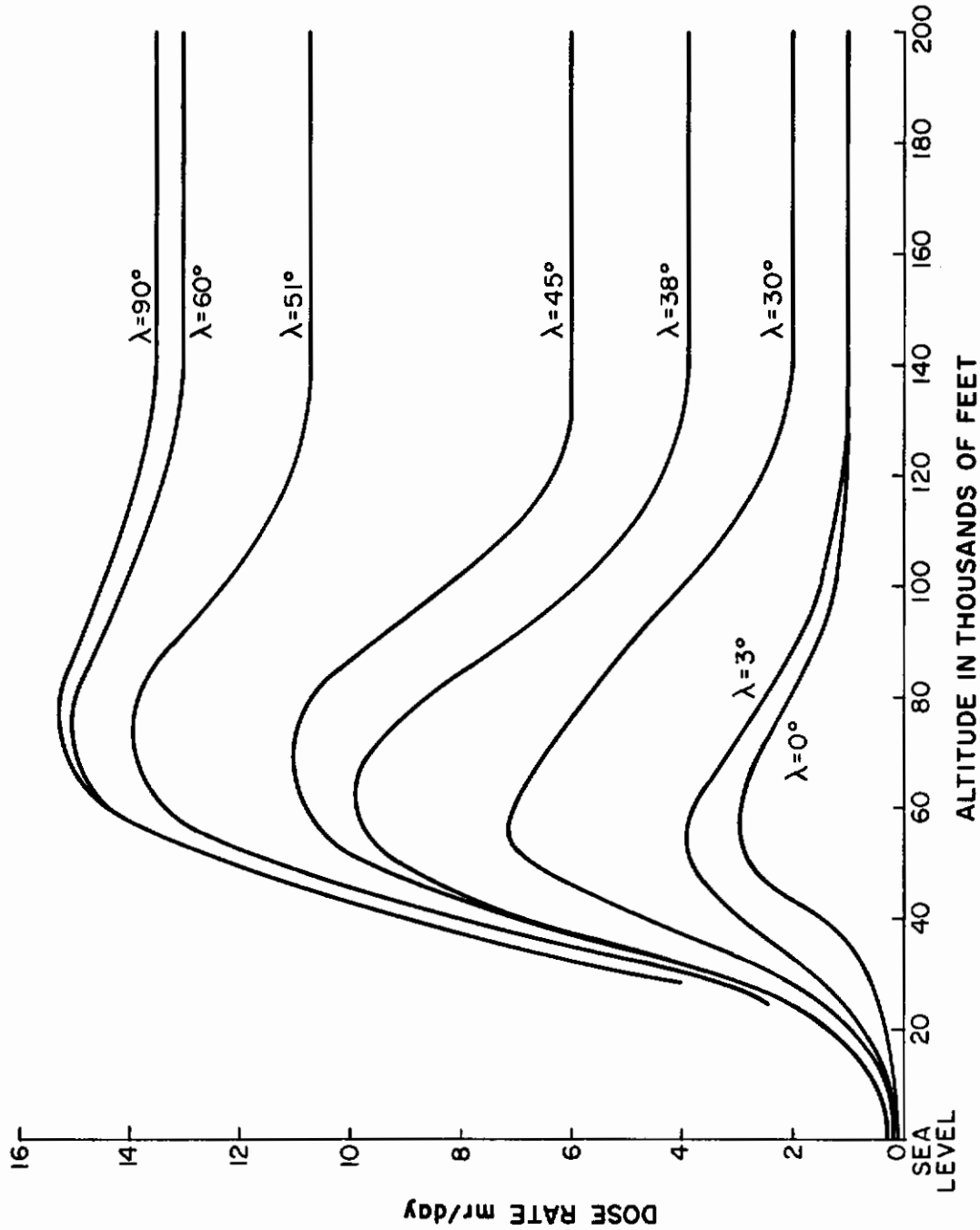

Figure 33. Cosmic-ray dose rates as a function of geomagnetic latitude and altitude during the period of solar activity maximum.

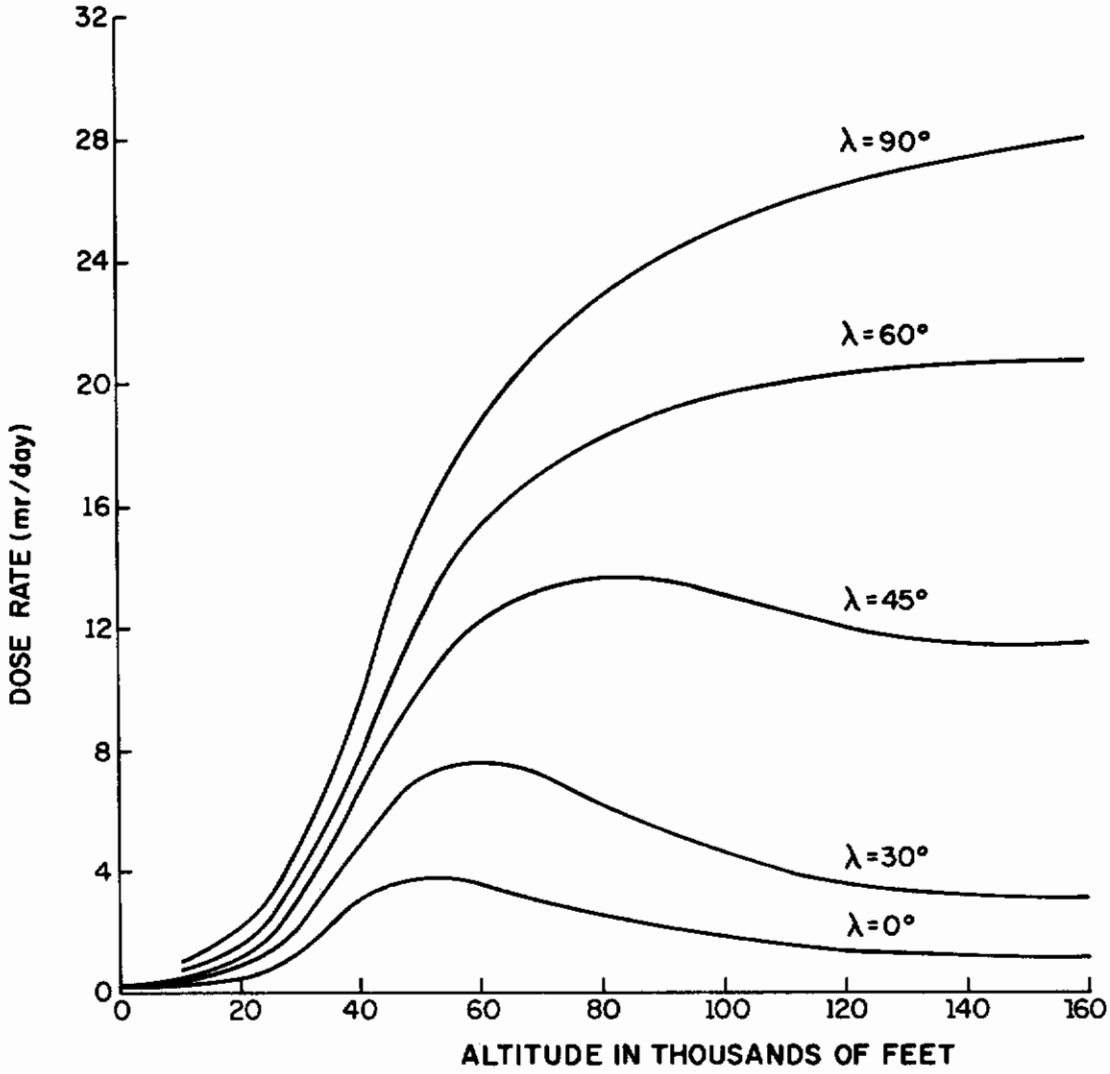

Figure 34. Cosmic ray dose rates as a function of geomagnetic latitude and altitude during the period of solar activity minimum.

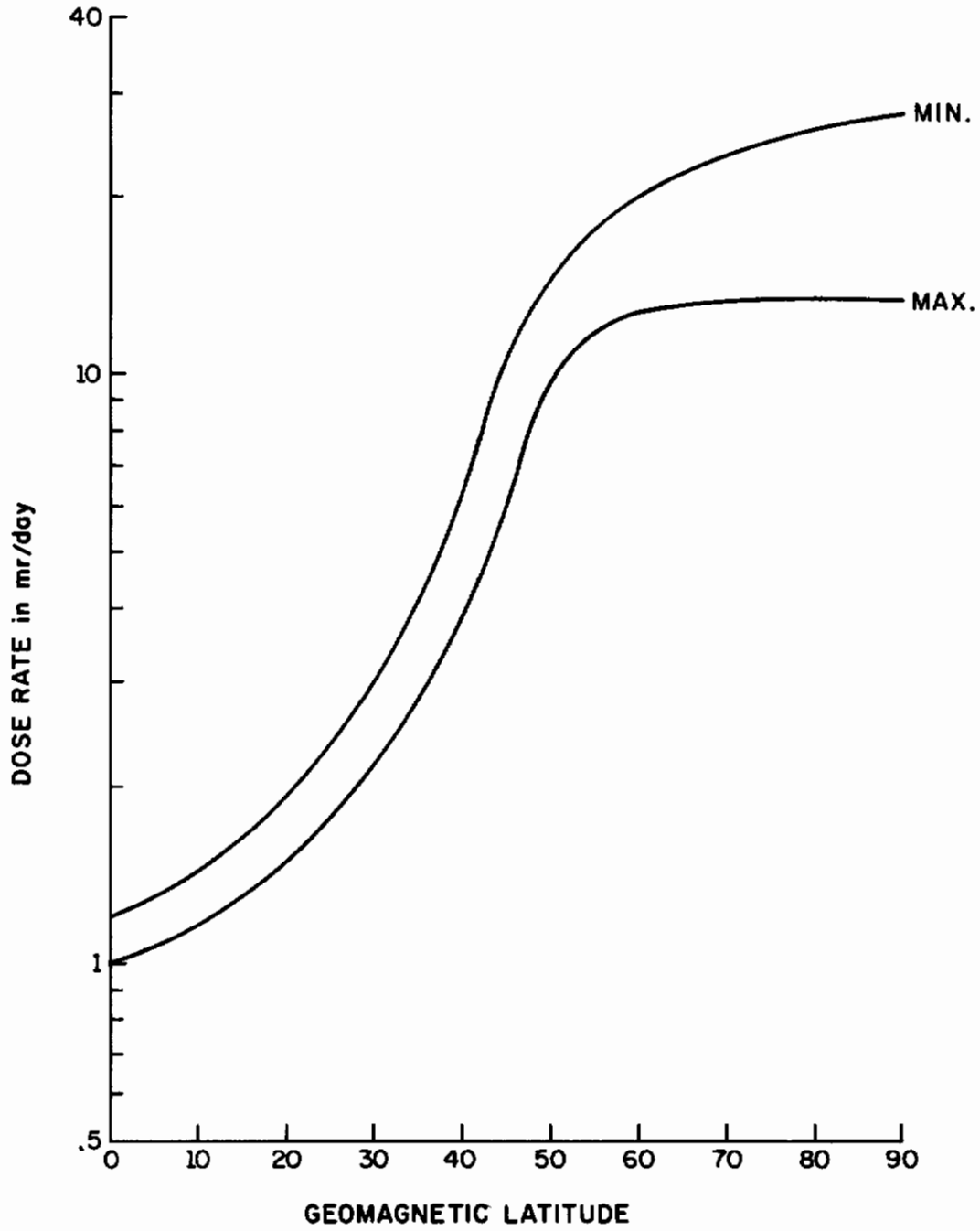

Figure 35. Cosmic-ray dose rate above the atmosphere as a function of geomagnetic latitude during solar maximum and minimum.

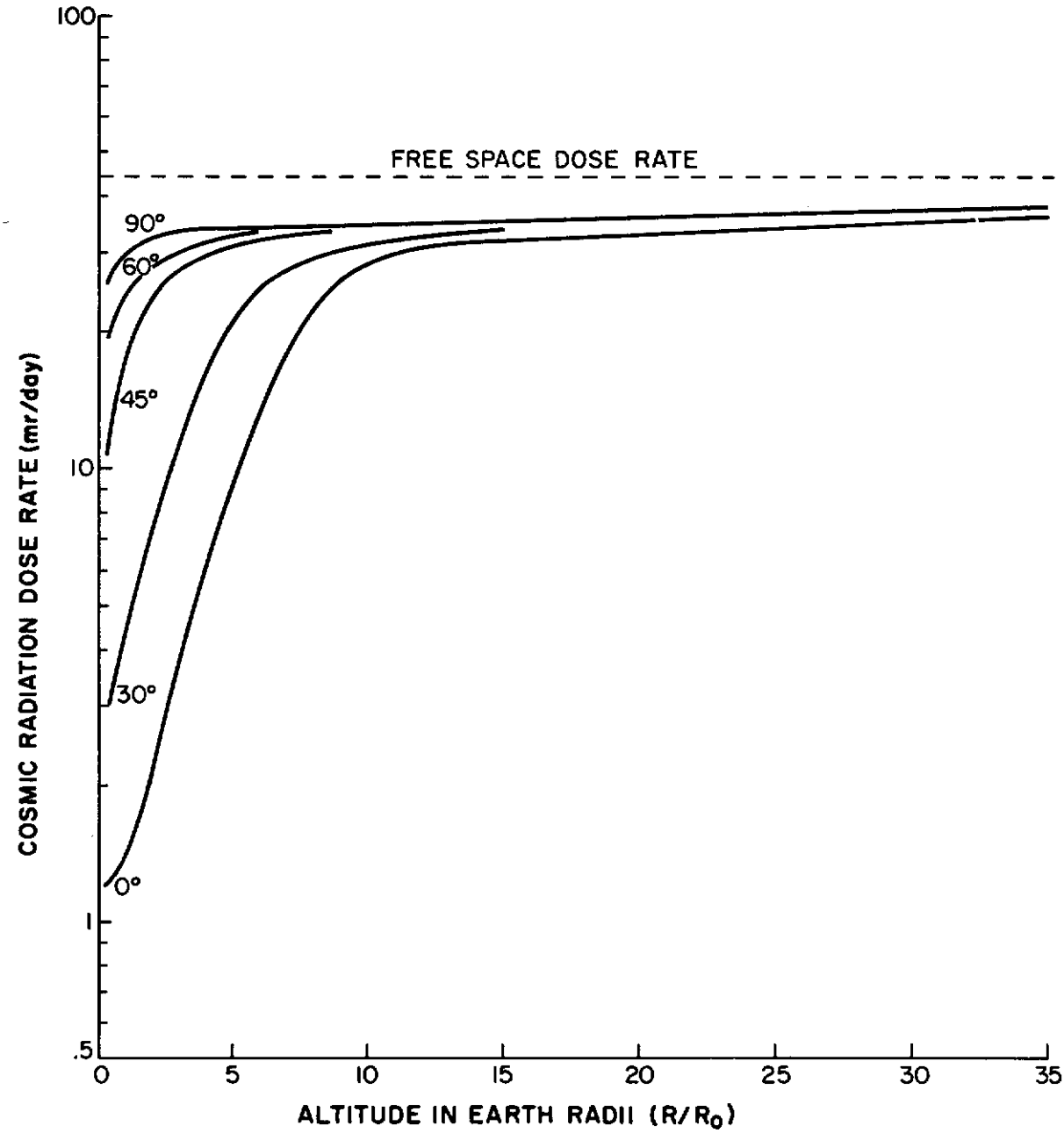

Figure 36. Cosmic radiation dose rate as a function of geomagnetic latitude for high altitudes during the period of solar activity minimum (altitude in earth radii (R/R_o) where $R_o \simeq 4000$ miles).

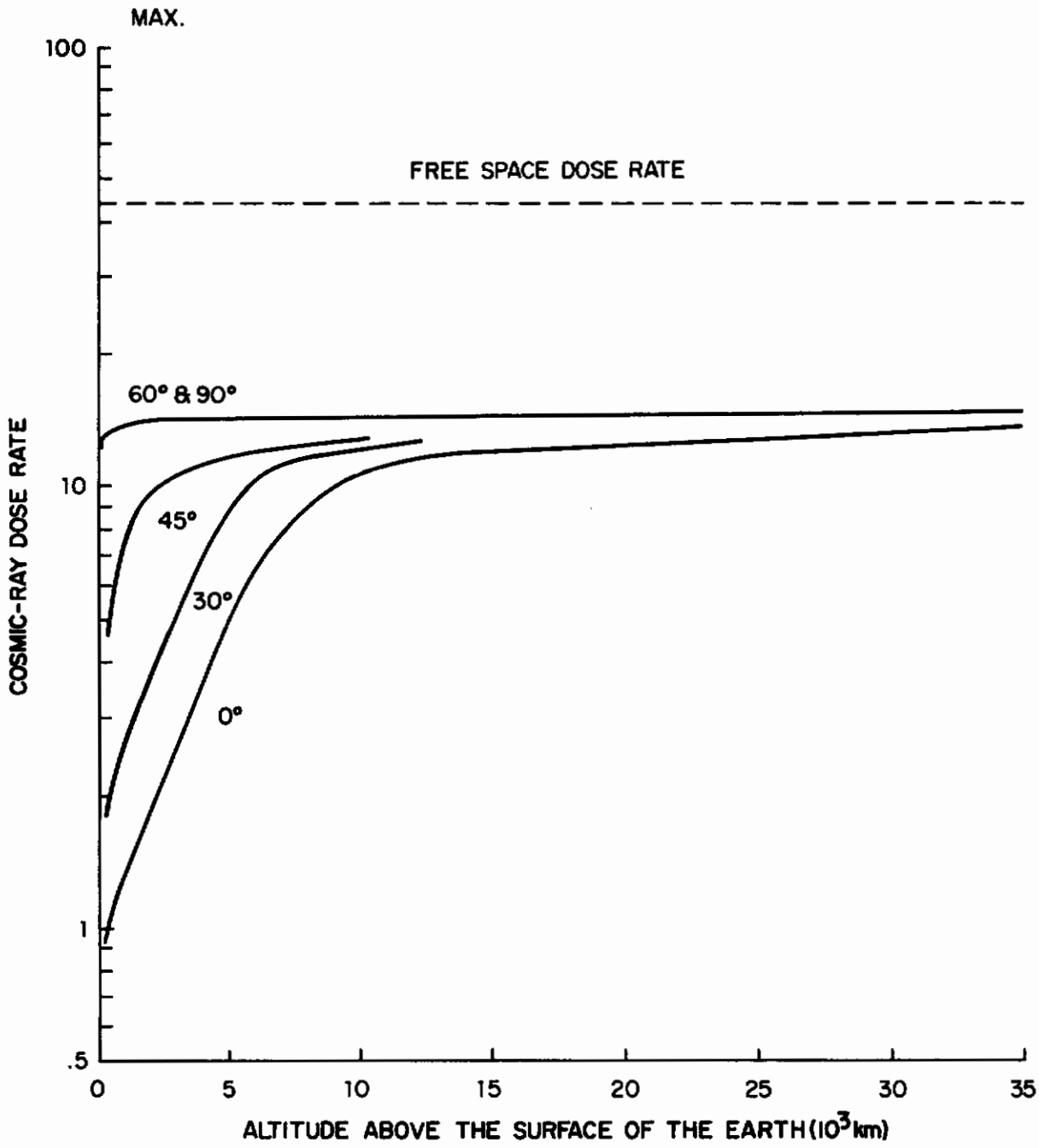

Figure 37. Cosmic radiation dose rate as a function of geomagnetic latitude for high altitudes during the period of solar activity maximum.

energy component. Therefore, these modifying variations are very important from the standpoint of radiation hazards in space flight.

We know today that the primary cosmic ray intensity does undergo pronounced variations, especially in the low energy portion of the spectrum. These characteristic variations in intensity are rather closely correlated with solar and geomagnetic activity, and it is generally believed that this relationship exists because of the modulation of the primary flux by changing magnetic and electric fields in interplanetary space. The galaxy is filled with an isotropically distributed cosmic ray field, but before this radiation reaches an observer on the earth the spectrum and intensity is modified by this solar controlled mechanism. There are numerous primary intensity variations, such as variations extending from seconds to eleven-year periods, amplitude variations from barely detectable fluctuations to changes of more than a factor of two. All of these variations can be categorized as either recurring (periodic) or nonrecurring (nonperiodic) types. Among the recurring types are the eleven-year intensity variations associated with the solar sunspot cycle and the solar diurnal variations. Among the nonrecurring types are the Forbush-type intensity decreases associated with the great magnetic storms and the quasi-periodic 27-day variations.

The Eleven-Year Intensity Variation

It was first observed by Forbush[18] that overriding all of the intensity-time variations, there exists a pronounced trend in the primary radiation intensity that is associated with the solar activity cycle and that there was an anticorrelation between the solar sunspot cycle and the cosmic ray intensity. It is now known that this phenomenon is energy dependent. Figure 38 shows the Zurich sunspot number as a function of time,[27] and Figure 39 shows the anticorrelation between the sunspot number and the cosmic ray intensity.[26] There has not as yet been found any relationship between the magnitude of the Zurich sunspot number and the magnitude of the cosmic ray intensity changes during the solar cycle.

Spectral changes in the primary proton radiation which occur between the period of maximum solar activity and minimum solar activity, i.e., maximum sunspot number and minimum sunspot number, from 1948 to 1954, can be understood if the primary spectrum is represented by the function:

$$J = \left(\frac{pc}{Ze}\right)^{\gamma} ,$$

Where Ze is the charge of the primary particle and p is its momentum.

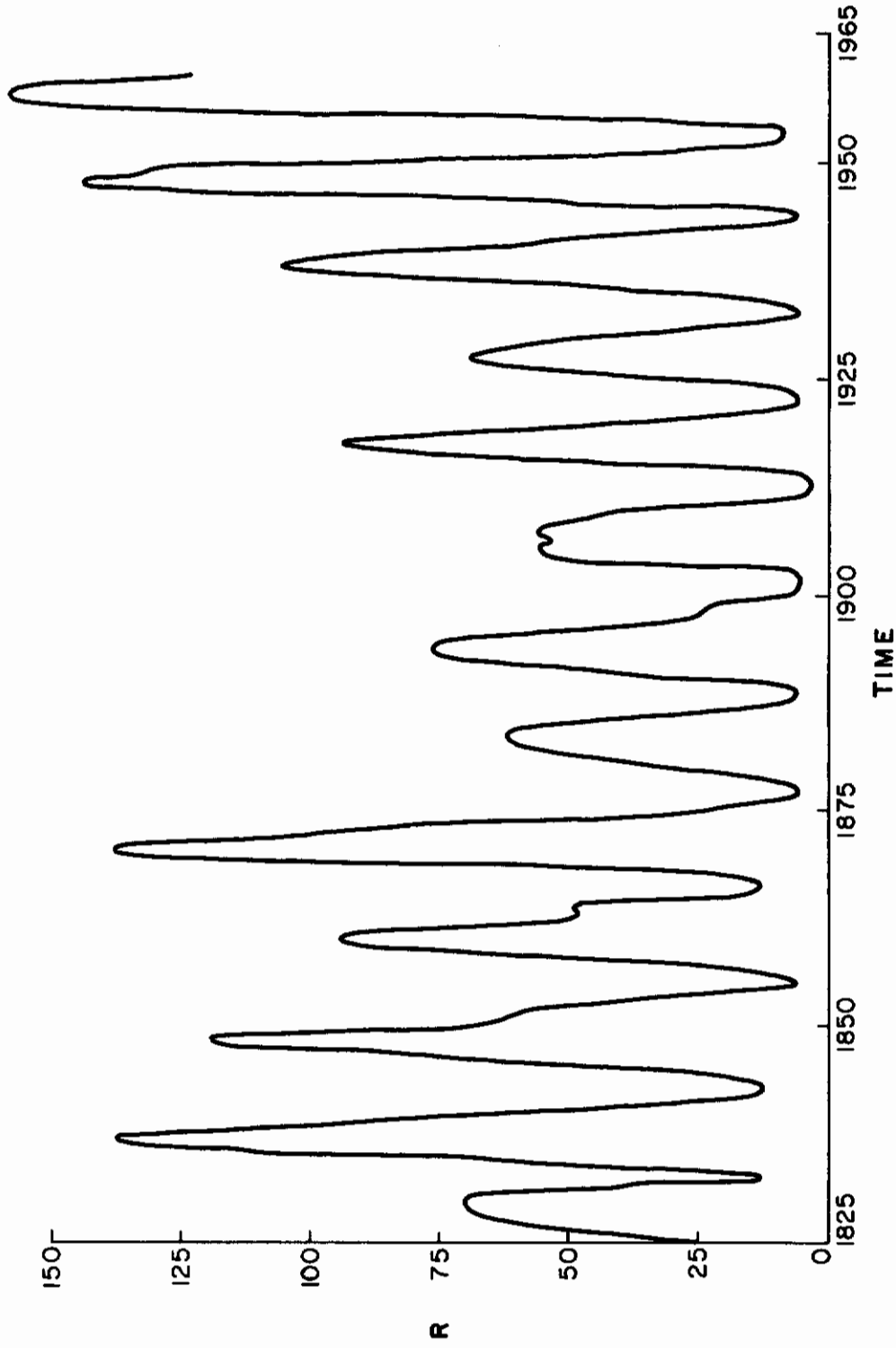

Figure 38. The Zurich sunspot number, R, versus time.

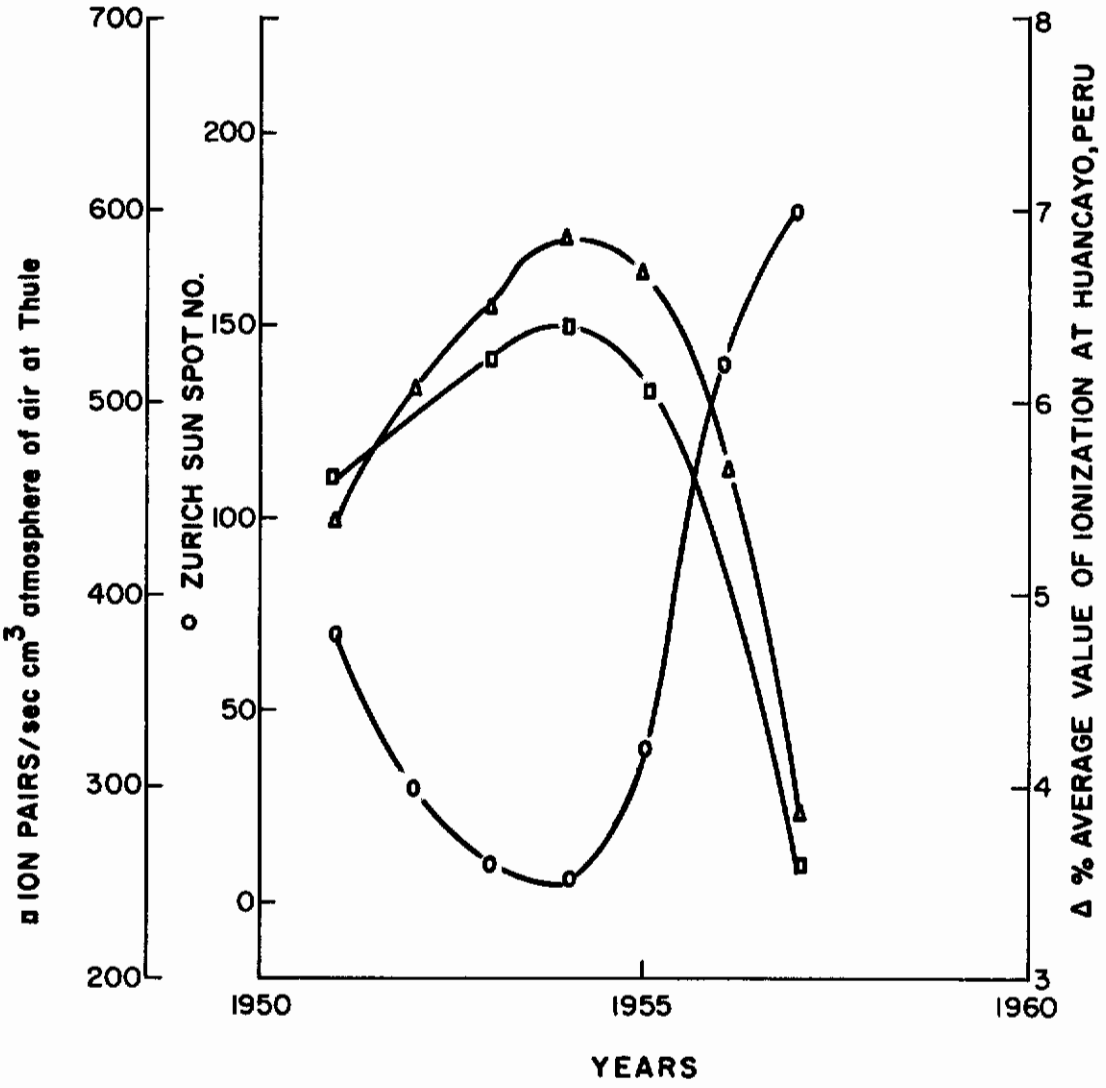

Figure 39. The anticorrelation between the Zurich sunspot number and the cosmic ray intensity.

In 1948 (solar maximum) the primary energy spectrum had an exponent of $\gamma = 2$. From 1948 to 1954 (from solar maximum to solar minimum) the change in γ was $\Delta\gamma = +0.7$. Again from 1954 to 1958 (from solar minimum to solar maximum) γ changed from 2.7 back to 2. The integrated flux from one Bev/e rigidity upward changed approximately 60 percent between 1954 and 1958. The magnitude of the intensity change amounted to almost a factor of 3 of the primary radiation between solar maximum and solar minimum.[56]

The low energy particle spectrum changes throughout the solar cycle. The so-called particle energy cutoff, which had in earlier years been assumed to be invariant in time, is shown now to change between solar maximum when the energy cutoff is present to solar minimum when the energy cutoff completely disappears. This phenomenon is not due to changes in the earth's geomagnetic field but is controlled by a periodic solar disturbance. During the periods of the minimum of solar activity (minimum sunspot number, 1954) there is no low energy cutoff with the spectrum extending down to and below about 0.15 Bev with an enhancement of about a factor of 2 of the total galactic intensity. However, during periods of maximum of solar activity and maximum sunspot number (1958) a low energy cutoff does appear with an absence of nonrelativistic particles with energy below about 0.6 to 0.8 Bev. A peak also appears in the differential spectrum at about one Bev with the spectrum above about two or three Bev essentially undisturbed. The total galactic intensity, of course, decreases tremendously. The primary proton flux at solar maximum (1937) was 1000 particles/m^2/sec/ster, in 1951 it was 1400 particles/m^2/sec/ster, and in 1954 solar minimum the flux was 2400 particles/m^2/sec/ster. This illustrates the remarkable variability of the very low-energy primary cosmic rays.*

In addition, a detailed study of the α-particle spectrum has shown that the total flux of primary α-particles decreased at sunspot maximum (1958) by a factor of two from its sunspot minimum value in 1954. The decrease is more pronounced at lower energies and is therefore reflected in a somewhat flatter energy spectrum at sunspot maximum than at sunspot minimum. The effect on the integral energy spectrum of α-particles is shown in Figure 40, which is a plot of the spectra obtained at sunspot minimum (1954) and at sunspot maximum (1957-58).

The integral energy spectra at $E > 500$ Mev/Nucleon may be represented by:[51]

$$N(>E) = C/(m_o c^2 + E)^n ,$$

* See reference nos. 46, 66, 67, and 79.

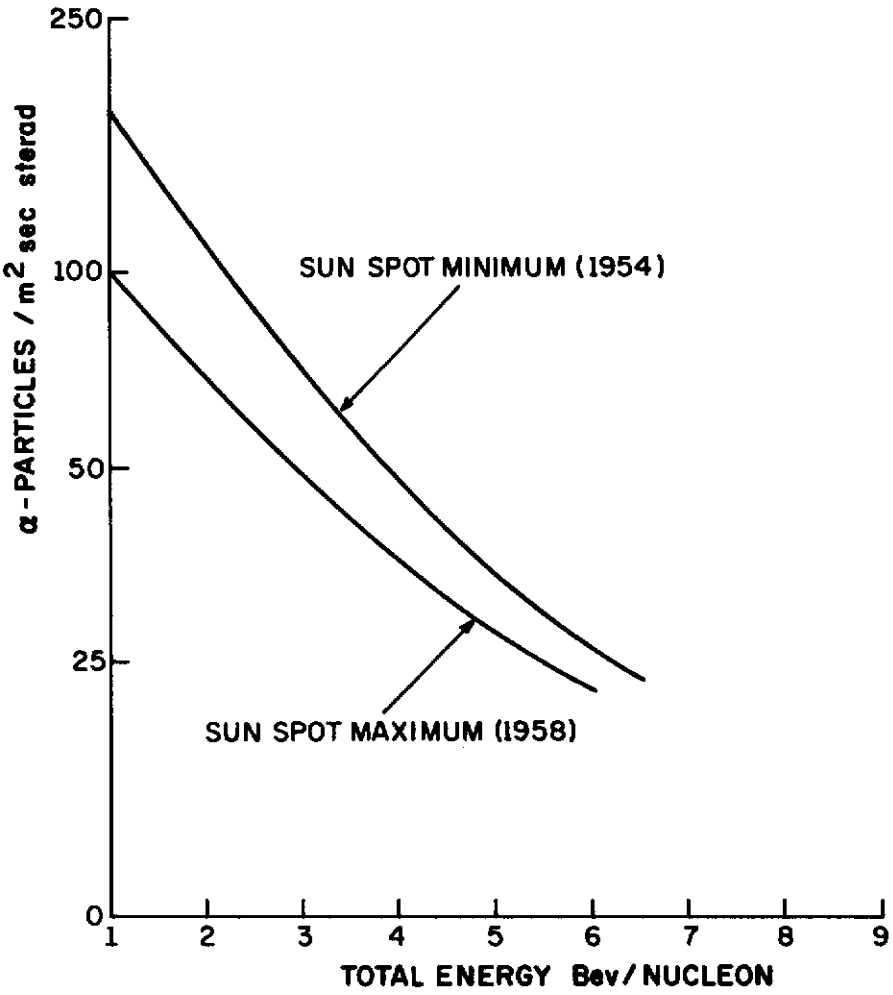

Figure 40. The integral energy spectrum of alpha particles obtained at solar sunspot maximum and minimum.

where at sunspot maximum C = 185 ± 30, and n = 1.17 ± 0.14. At sunspot minimum over the same range of energies, C = 360 ± 40 and n = 1.48 ± 0.12. It can be seen that the slope of the integral energy spectrum at sunspot maximum is appreciably smaller than at sunspot minimum.

Experiments have shown that the solar cycle modulation is produced by a depression of all cosmic rays and not by the imposition of a sharp cutoff, as was previously thought. The so-called "knee" in the galactic cosmic ray spectrum is produced by the form of the incoming primaries which has a maximum in the differential energy spectrum at about 300 Mev/nucleon at sunspot minimum and about 500 Mev/nucleon at sunspot maximum. Although the reason for the maximum in the differential spectrum is not yet understood, it is quite clear that it is not produced by a sharp magnetic cutoff.

Figure 41 shows the differential rigidity spectrum of both protons and α-particles at sunspot minimum and maximum. The spectra of both protons and α-particles are alike at maximum and minimum except the α-particle spectrum is multiplied by 6.5. Since particles of the same rigidity are modulated in this way, there is this suggested magnetic modulating mechanism.

A composite picture of the eleven-year variation is as follows: During years of low solar activity, one observes an energy spectrum without any low energy cutoff and a power law with α = 2.7. And in years of high solar activity one finds a spectrum with a definite low energy cutoff and power law with α = 2, with a decrease in the total cosmic ray intensity. Figure 42 shows these composite changes in the spectrum which occur between the minimum activity (1954) and the maximum solar activity (1958).[54] The primary cosmic ray spectrum obtained at solar sunspot minimum probably represents the true galactic cosmic ray spectrum with the absence of the solar modulation influence.*

The Solar Diurnal Variation

In the discussion thus far we have considered the primary cosmic ray flux at the earth to be isotropic at all rigidities, but in fact a small spatial anisotropy of the primary radiation presumably caused by a large-scale polar dipole field in combination with the rotation of the earth leads to a small amplitude daily variation in the primary intensity. The diurnal variation,[61] shown in Figure 43, has an intensity amplitude change associated with it which is very small, of the order of 0.1-0.2 percent.

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* See reference nos. 44, 64, and 74.

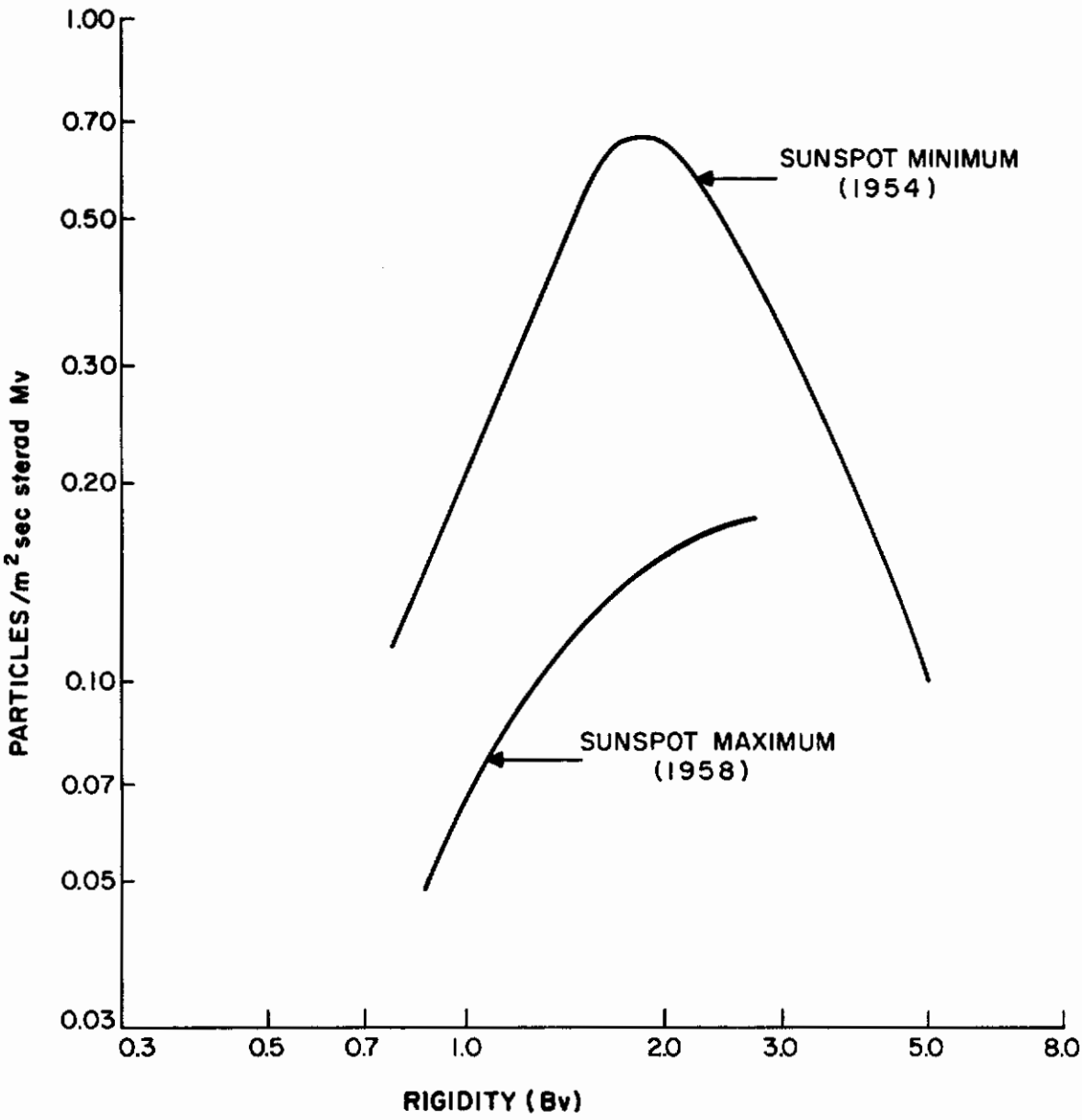


Figure 41. The differential flux of protons and alpha particles at the time of sunspot minimum and maximum. The alpha particle spectrum is multiplied by 6.5.

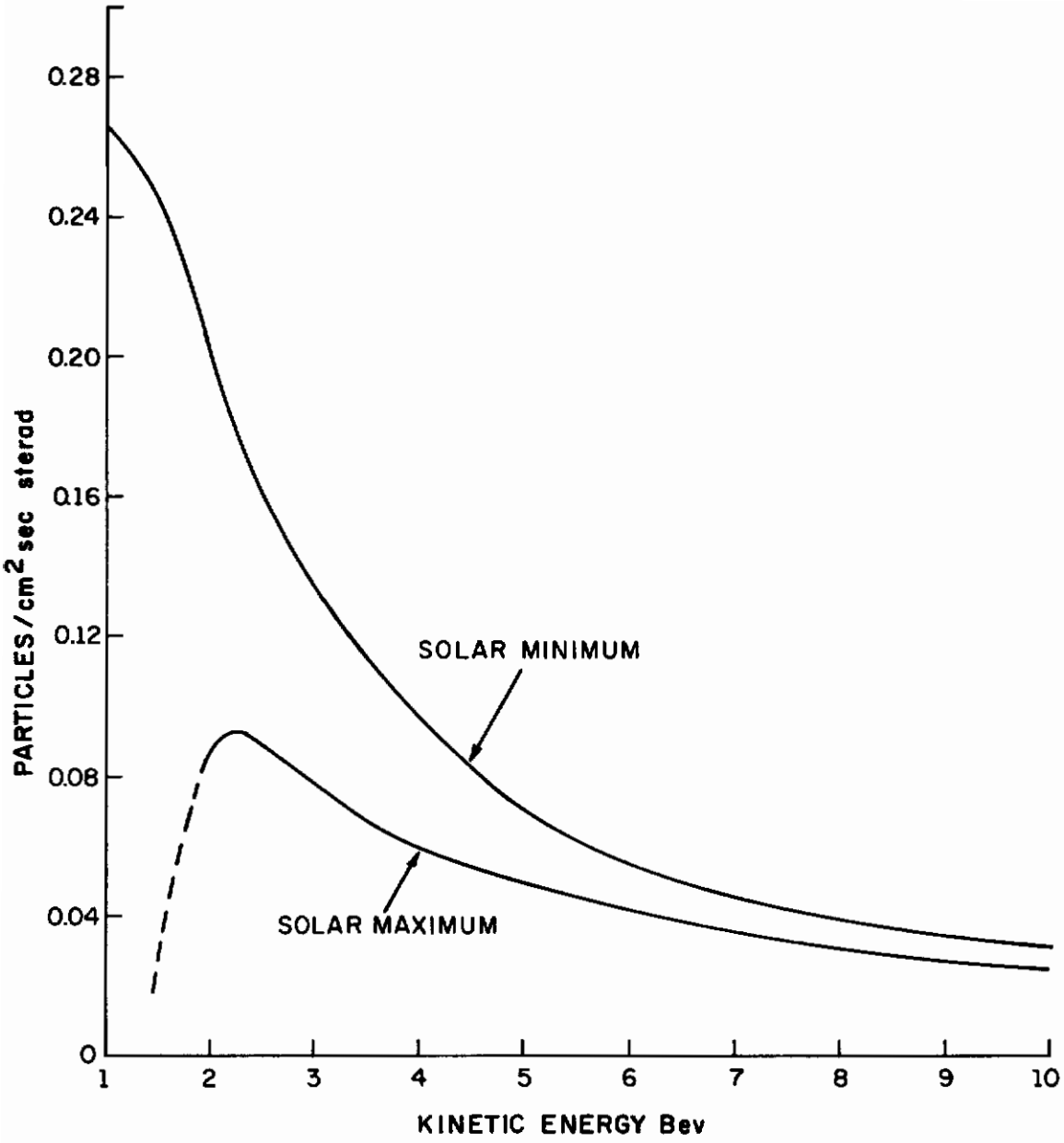


Figure 42. Composite changes in the primary spectrum occurring between solar minimum and maximum.

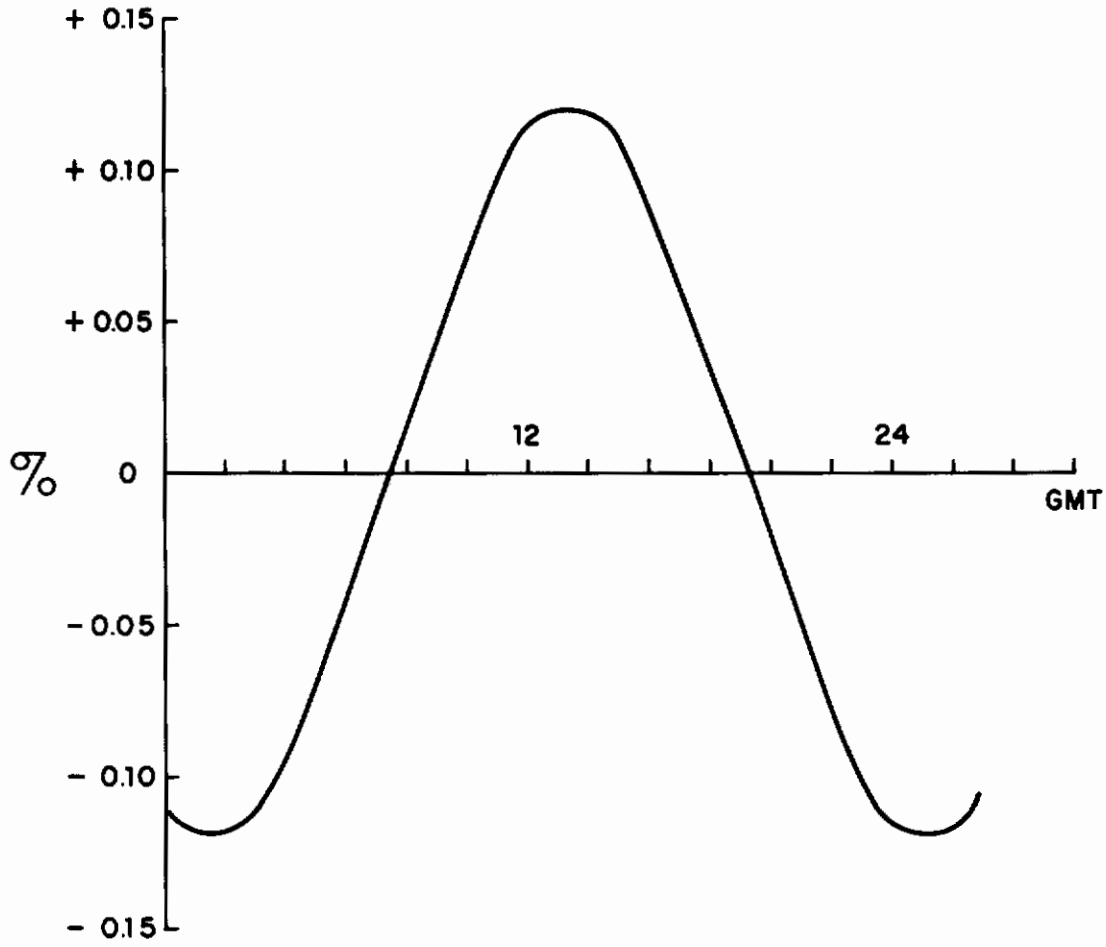


Figure 43. The yearly mean of the daily cosmic ray variation.

It seems to be enhanced during periods of solar magnetic activity and varies in a periodic manner during the solar activity cycle. The time of the maximum of the variation seems to occur shortly after noon or around 0540 hours, local time. Since this variation is quite small it could be of little consequence as far as radiation hazards are concerned.[15, 55]

MAGNETIC STORM EFFECTS

There are two types of transient magnetic behavior: (2) The great world-wide storms characterized by a sudden increase in horizontal field intensity which lasts for an hour or so, followed by a rapid decrease to a value below normal. The field then recovers slowly over a period of days. Such storms may occur about 20 times a year, but without any definite regularity. (b) The smaller storms have a tendency to recur with a 27-day periodicity connected, presumably, with the rotational period of the sun.

It is generally believed that the geomagnetic disturbances are produced by corpuscular beams from the sun. In particular, the magnetic effects appear to be correlated with active regions of the sun.

All of the cosmic ray intensity changes associated with magnetic storms appear to be caused by the deflection of primary particles in the energy interval 0 to 5 Bev/nucleon by the solar corpuscular beam. In addition, this beam is responsible for "sweeping out" many of the electrons in the Heaviside layer and disrupting the structure in the outer Van Allen radiation belt. As a side result, electrons are "dumped" into the earth's atmosphere causing the well-known aurorae at both poles.[72]

The Forbush-Type Intensity Decreases

At the time of a great magnetic storm it frequently happens that the storm is accompanied by a world-wide decrease in the primary cosmic ray intensity. These decreases, first described by Forbush in 1938, are quite striking with an average intensity decrease on the order of 5-10 percent in amplitude. A unique feature of these events is a sharp decrease in the primary beam that may occur at rates up to 3 percent or higher per hour and produce overall decreases of intensity as high as 30 percent. The recovery of this intensity decrease back to the pre-storm value has a "half-life" of the order of one to two days and sometimes longer. The spectral changes extend out beyond $\approx$50 Bev/c rigidity and are much less dependent upon particle rigidity than for the spectral changes in the eleven-year intensity variation. A typical event is shown in Figure 44.[66] Thus, the Forbush decreases are a temporary depletion of nonrelativistic particles from the average spectrum. The cause of these events is probably

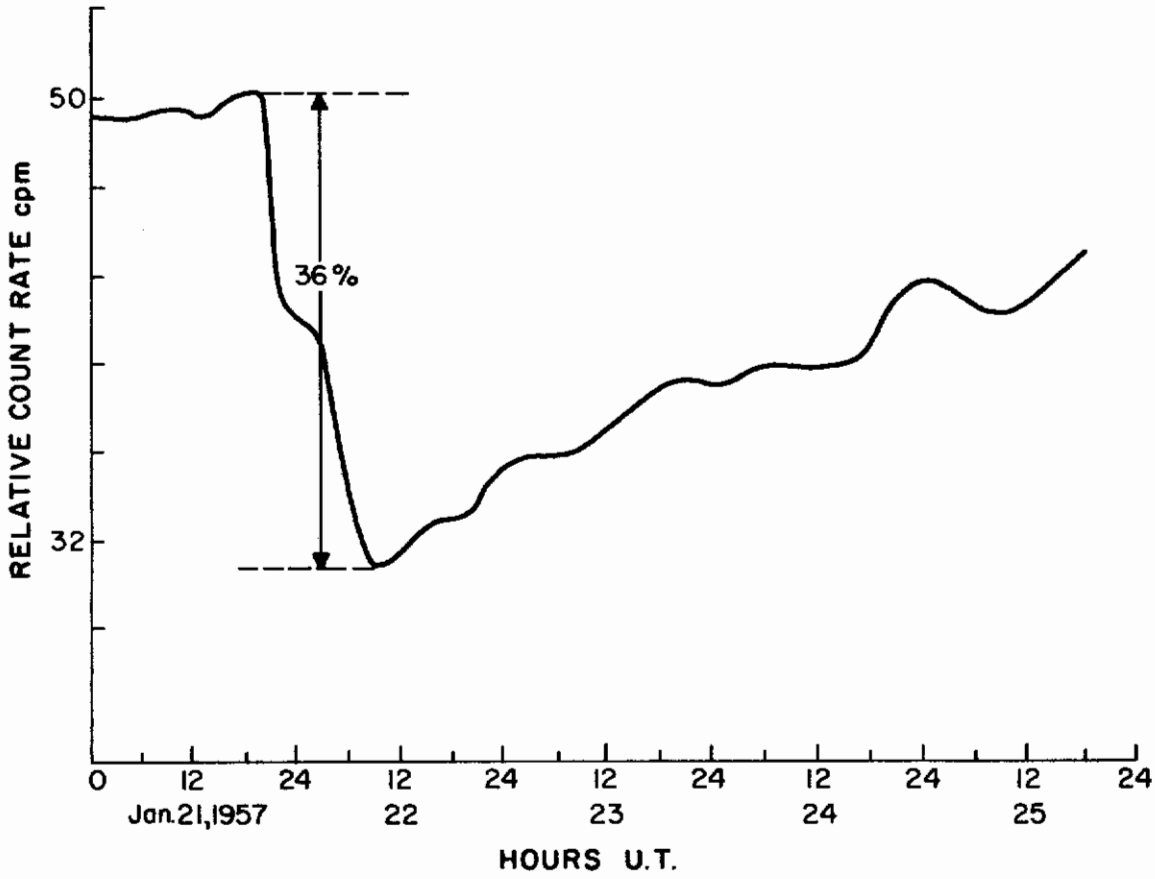


Figure 44. A typical Forbush-type decrease--characterized by a sharp decrease in primary intensity followed by a slowly rising increase back to normal.

connected with magnetic storms and must lie in the vicinity of the earth-sun system; perhaps it may be explained by the solar corpuscular beam modulation mechanism.* According to present models, these Forbush decreases are closely connected with the eleven-year cycle in intensity in that they are more prominent during solar maximum than during solar minimum. They are observed when the earth lies directly in the path of the outward-streaming material emitted by an active region on the sun. (see Figure 45.)

The tongue of plasma that erupts from the surface of the sun moves out across interplanetary space at a speed of about 1000 miles per second. The cloud drags with it lines of solar magnetic force, which are "frozen" into the cloud and are forced to move with it by the laws of electromagnetism. By the time this plasma reaches the vicinity of the earth's magnetic field, it has become weakened. However, it is still sufficiently strong to screen the earth partially from the galactic cosmic rays that normally bombard it. It is this screening effect that is responsible for the observed Forbush decreases.[35]

The Quasi-Periodic 27-Day Variation

The 27-day intensity decreases are phenomena basically similar to the Forbush decreases, but differ in that they have much smaller amplitudes and have a tendency to recur with a 27-day periodicity corresponding to the time it takes the sun to rotate around its axis. These variations are only present in years of enhanced solar activity.** Figure 46 shows the typical 27-day variation.

In general, then, the characteristics of the cosmic ray intensity modulation process can be explained in terms of a large-scale solar field of predominantly dipole character. This field contains small-scale irregularities acting as scattering centers and is occasionally very seriously distorted by outward-moving solar material. In particular, this model appears to be capable of giving a semi-quantitative account of the eleven-year cyclic variation, the Forbush-type decreases, and the solar diurnal variation.

In addition, one can interpret the relativistic spectrum of the cosmic radiation at solar minimum as representing the nonsolar spectrum of radiation as one would find outside the solar system. At solar maximum, therefore, one observes the resultant spectrum of particles at the earth as a consequence of the propagation through magnetic fields of solar origin and therefore is a solar modulated galactic beam.

* See reference nos. 55, 59, and 66

** See reference nos. 21, 55, and 58

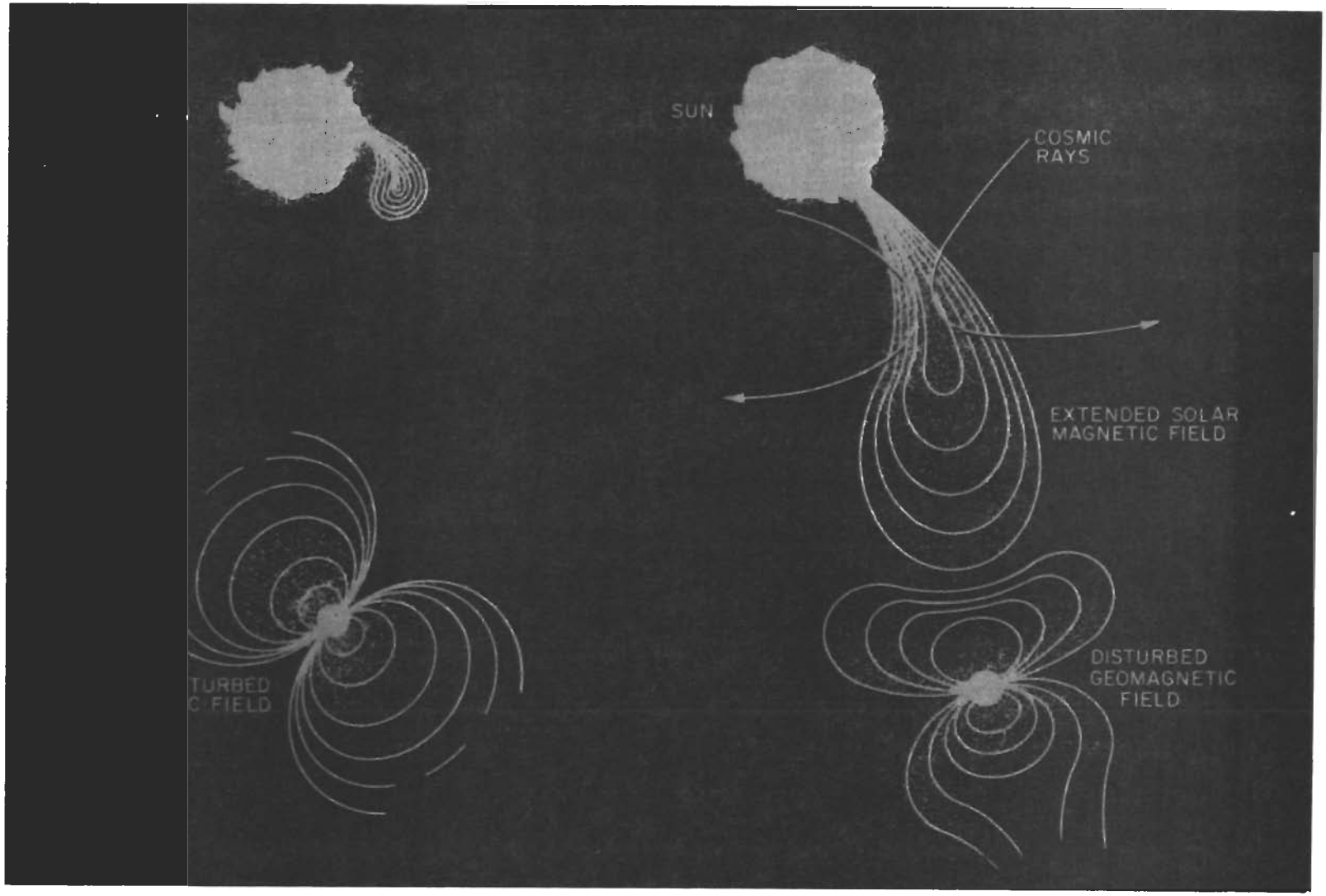


Figure 45. Interaction of the solar plasma with the earth's magnetic field causing increased deflection of galactic cosmic rays.

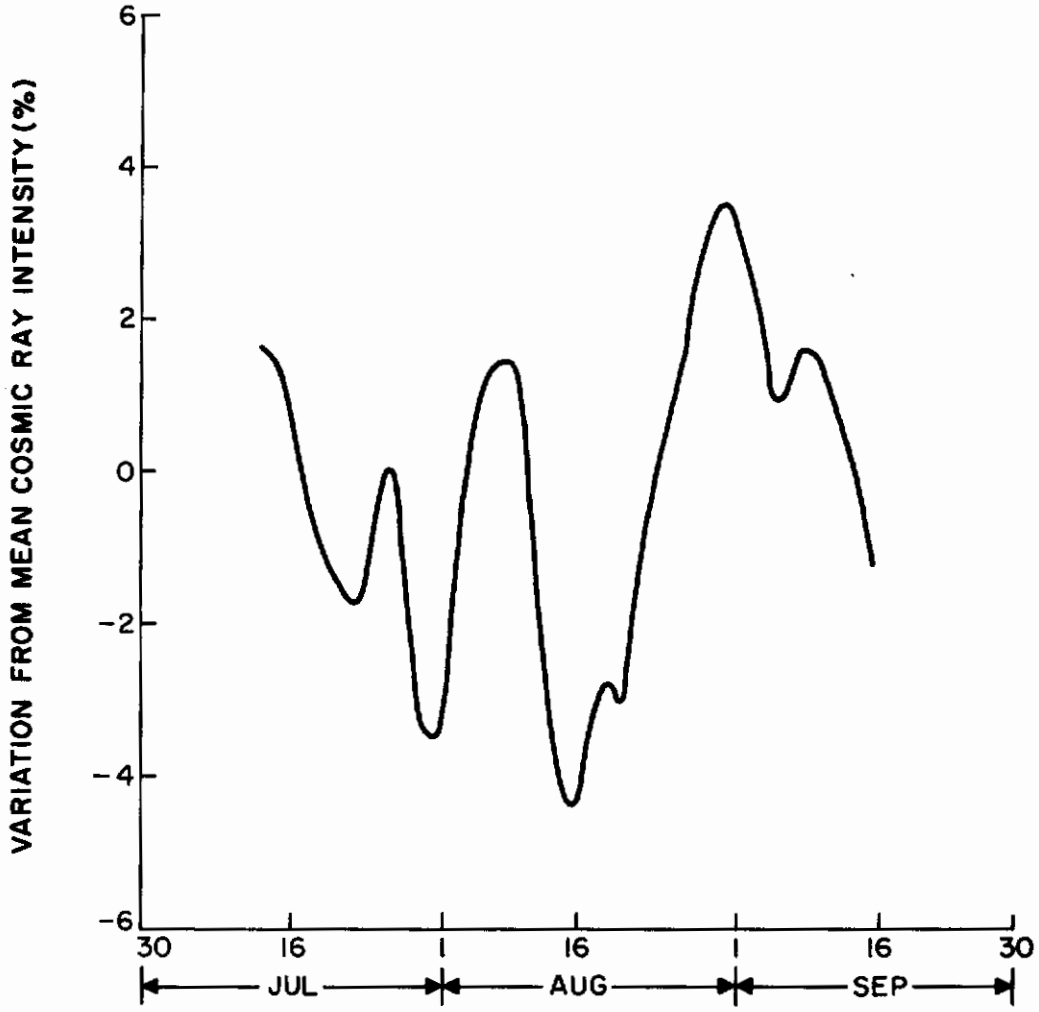


Figure 46. A typical 27-day cosmic-ray intensity variation.

The solar cycle modulation of cosmic rays is probably produced by the cloud of magnetic plasma ejected by the sun at high levels of solar activity. This magnetic cloud fills the solar system and deflects out low energy primary cosmic rays causing a depression in the cosmic ray intensity in the vicinity of the earth. The depression of cosmic rays occurs rather abruptly in the year or two preceding sunspot maximum and persists for some years after sunspot maximum. This turbulent magnetized cloud produces a screening of the earth by scattering low energy cosmic rays. The characteristics of the screen are governed by the solar activity. At sunspot minimum the screen is either temporarily removed or is made less impervious. Magnetic storms and the 27-day recurrences of decreases are caused by a localized stream of charged particles from the sun which enhance the earth's magnetic field and cause the observed decreases.* Using this galactic cosmic ray intensity modulation model as a basis, one can estimate the cosmic ray intensity as a function of distance from the sun in order to gain some insight into the expected intensities of Mars and Venus.[14] Figure 47 gives the resulting curves for two levels of solar activity.

GEOMAGNETIC EFFECTS

The magnetic field of the earth is essentially that of a dipole, which drops off with the inverse cube of the distance from the earth. The earth's magnetic field strength at the surface is only ~1 gauss, but the effects of the field extend for thousands of miles into space. It is this vast extent of the field that compensates for the low value and causes deflection of the incident cosmic ray primaries.

Primary particles that arrive vertically at the poles are moving parallel to the earth's field and are thus not deflected; but primaries arriving vertically at the equator are moving at right angles to the field and will experience a large deflection force unless their momentum exceeds a certain value. This critical or cutoff momentum depends on the charge of the particle as well as on the geomagnetic latitude. With sufficient accuracy, the smallest momentum, P, needed by a primary particle of an effective charge Z_{eff} to arrive or enter the atmosphere vertically or at the zenith at a particular geomagnetic latitude, λ, is given by:[25, 55]

$$P \approx \tfrac{1}{4} P_c Z_{eff} \cos^4 \lambda ,$$

where $P_c = 59.3$ Bev/c.

In order for one to interpret and understand the geomagnetic effect on primary cosmic rays within or outside the earth's atmosphere, one needs to know the motion of these charged particles in the earth's magnetic field. Since practically all the primary radiation consists of positively

* See reference nos. 55, 59, and 66.

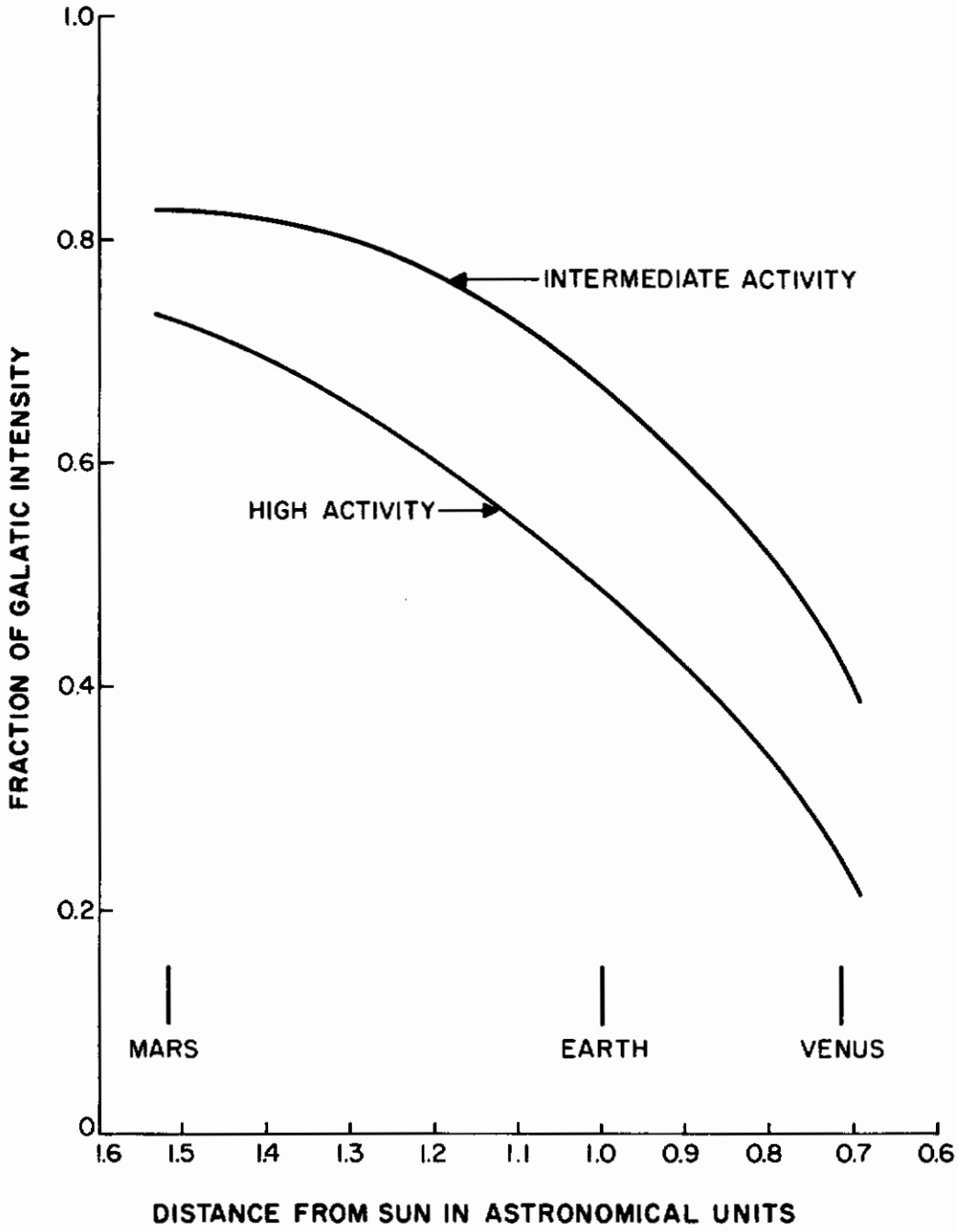


Figure 47. Theoretical solar modulation of cosmic ray intensity in interplanetary space.

charged particles, they will be affected by accelerations arising from interactions with the earth's geomagnetic field. The quantity (parameter) which expresses the magnitude of this effect is known as the Magnetic Rigidity, M, which determines whether a fast-moving particle is admitted or rejected by a magnetic field. It is directly proportional to the component of particle momentum which is perpendicular to the magnetic field. This can be expressed as:[5]

$$M = HR = Pc/Ze \ ,$$

where

H = magnetic intensity of the field;
R = radius of curvature of the particle in the field;
P = momentum of the particle;
c = velocity of light;
Ze = electric charge carried by the particle

Thus, there exists for a given geomagnetic latitude and direction of arrival a critical or cutoff value of the magnetic rigidity, M_c, such that all particles with $M > M_c$ can reach the earth from space and their flux is the same as if the earth's magnetic field were absent, since the primary cosmic rays are isotropically distributed in space. On the other hand, the flux of particles with $M < M_c$ is zero.

The relationship between the magnetic rigidity and the kinetic energy of a fast-moving particle is given by:

$$M = \frac{1}{Ze} \left[E^2 + 2m_0 c^2 E\right]^{\frac{1}{2}} \ ,$$

where

M = rigidity,
E = kinetic energy,
m_0 = rest mass of proton,
Ze = charge on particle,
c = velocity of light.

Figure 48[42] shows the relationship for large kinetic energies between magnetic rigidity and the kinetic energy.[25]

Figure 49 shows the cutoff rigidity for protons as a function of λ in the vertical direction of arrival as well as arrival at 45°E and 45°W.* The horizontal line indicated in Figure 49 is an unknown field producing

* See reference nos. 53, 62, and 63.

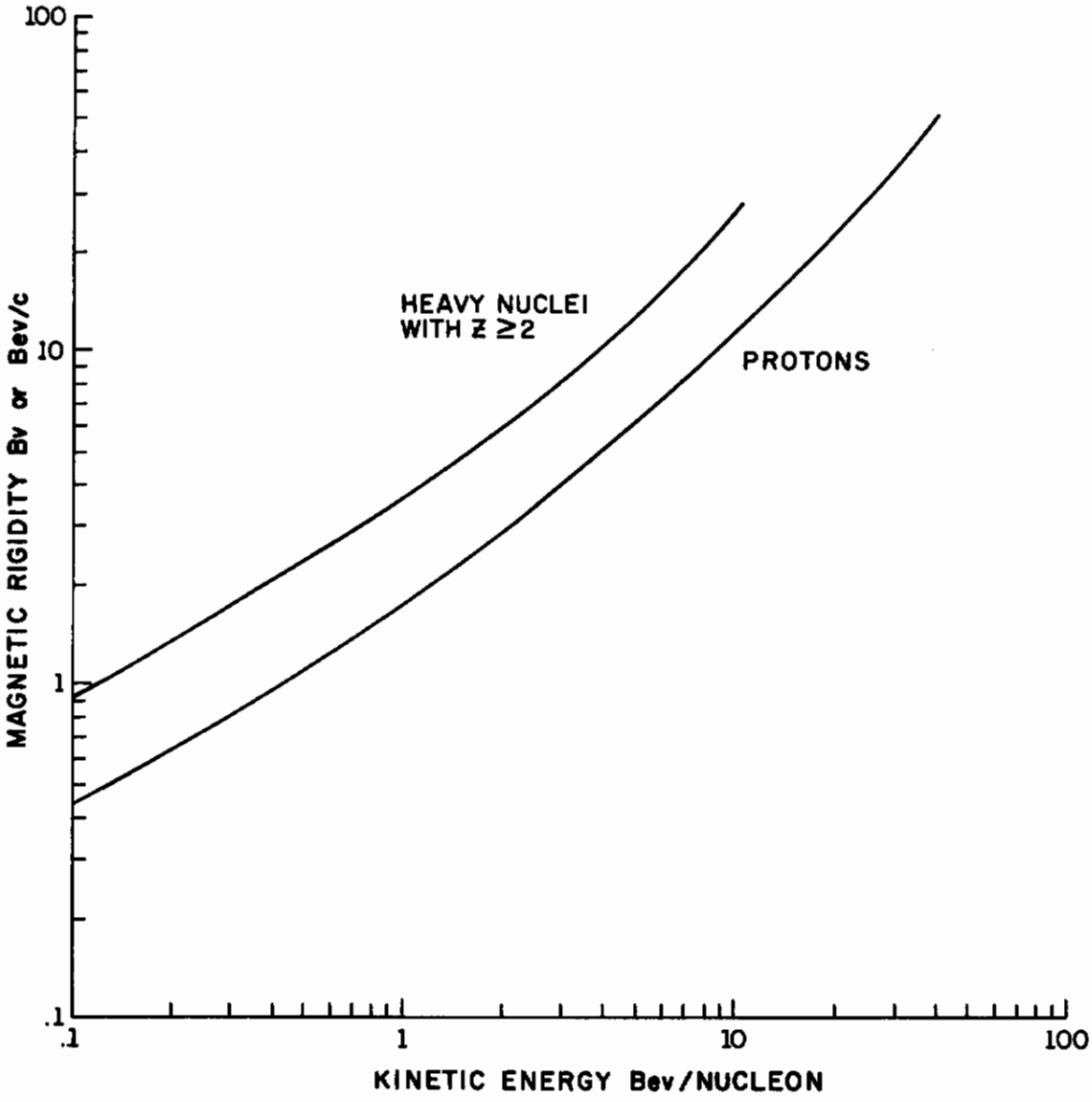


Figure 48a. The relationship between a charged particle's magnetic rigidity and kinetic energy.

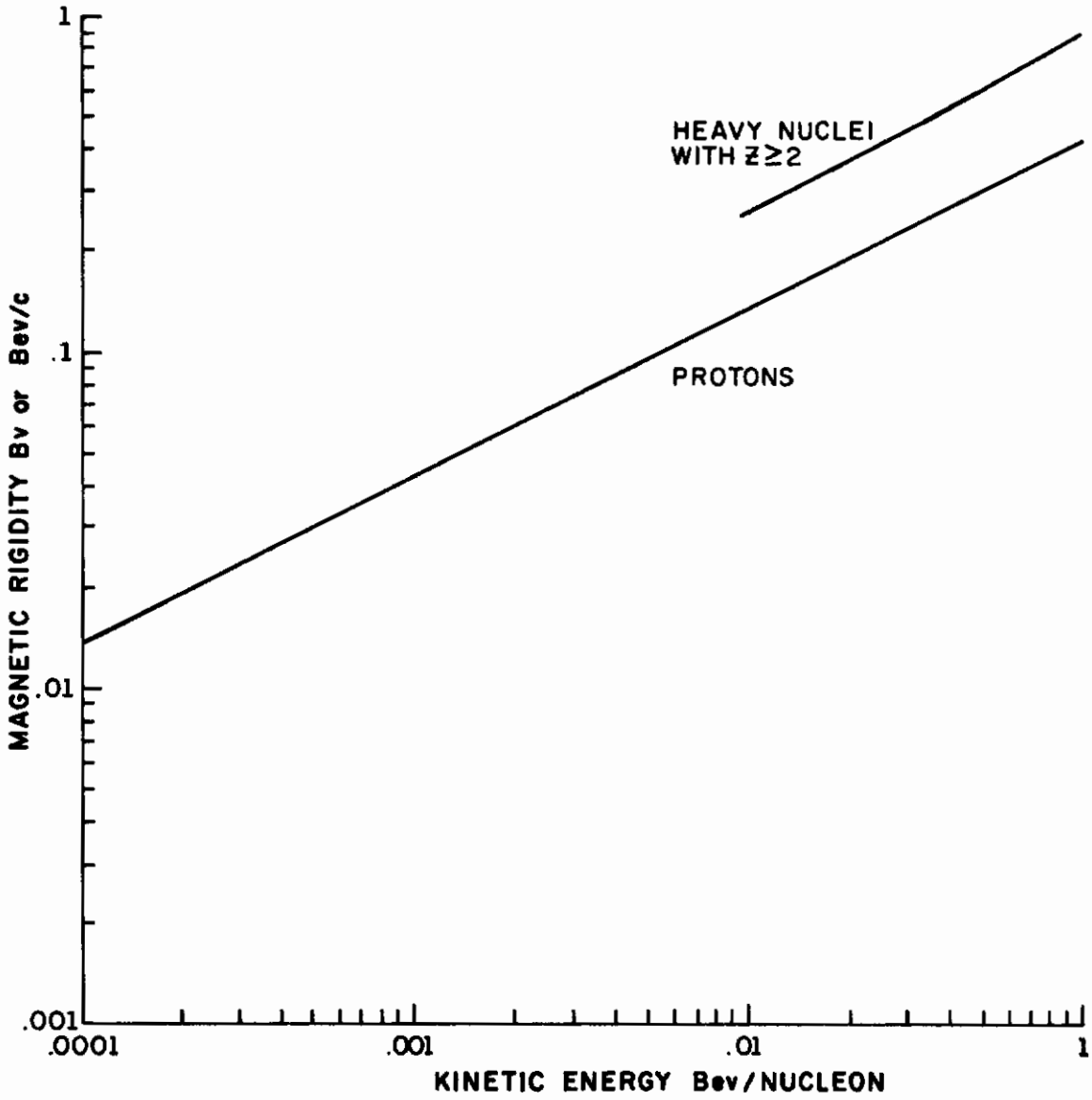


Figure 48b. The relationship between a charged particle's magnetic rigidity and kinetic energy.

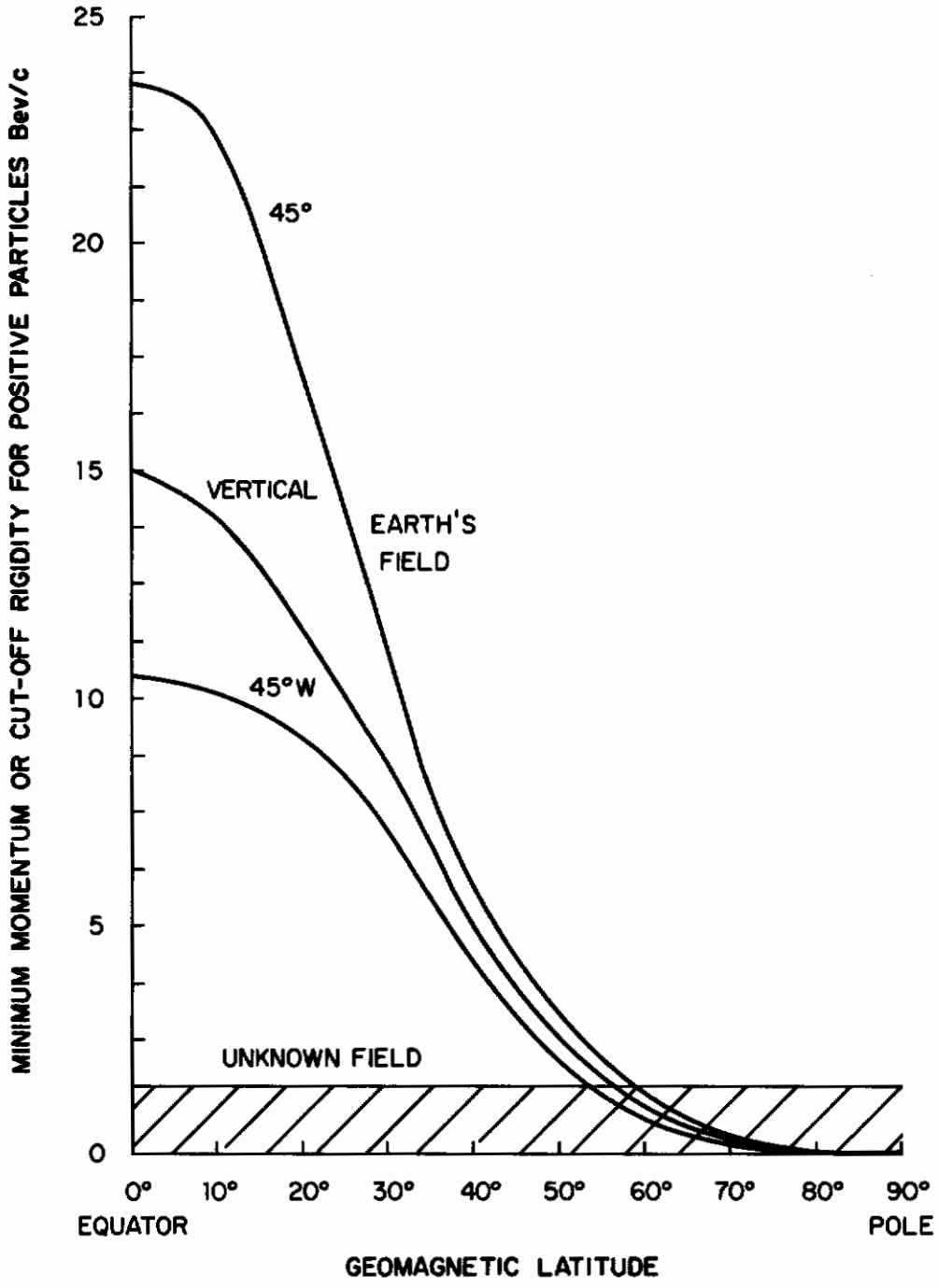


Figure 49. Dependence of cutoff rigidity as a function of geomagnetic latitude at 45°E, 45°W and the vertical directions of arrival.

residual cutoff in the polar region. The curve indicates that a magnetic shielding influence of unknown origin seems to be superimposed on the normal geomagnetic field taking over the latter's cutoff function at about 55°. Specifically, a solar dipole field reaching as far out as to the earth's orbit has been invoked as causing the "knee" in the latitude curve.

Figure 50[26] shows the maximum momentum of arrival for protons in the east-west plane as a function of zenith angle or direction of arrival of the incident particle.

The geomagnetic cutoff energies for primary protons (as shown in Figure 51)[50] and for the other primary cosmic ray constituents incident at various angles can be represented by a gaussian distribution involving a function of the geomagnetic latitude and angle of incidence of the fast-moving particles.

Qualitatively, then, all primary particles can penetrate vertically to the earth's atmosphere at the earth's geomagnetic poles. However, in the equatorial plane, an incident vertical primary needs a minimum momentum for entry to the atmosphere of about 15 Bev/c, as shown by Figure 49. For other directions of entry rather than vertical, the particle's limiting momentum will be a function of the zenith angle direction. Table X shows the limiting momentum for positively charged particles incident from various zenith angle directions such as the east ($\theta = 0°$), the zenith ($\theta = \pi/2$), and the west ($\theta = \pi$).[25]

TABLE X

Minimum Momentum For A
Primary To Enter The Earth's Atmosphere

Incident Direction	Geomagnetic Latitude (λ)	Limiting Momentum (Bev/c)
From East	0	60
	45	4.6
	90	0
From Zenith	0	15
	45	3.7
	90	0
From West	0	10
	45	3.1
	90	0

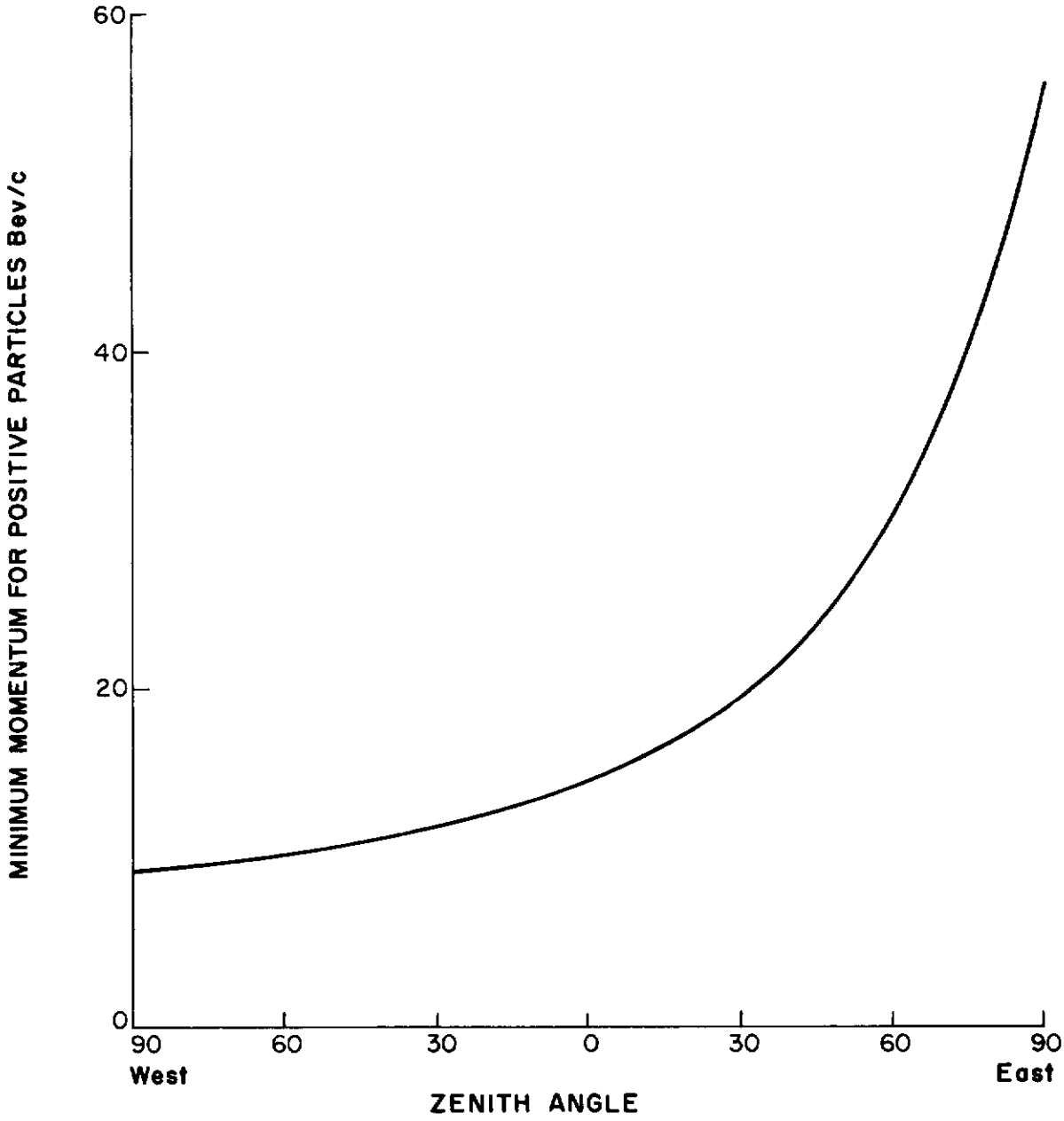


Figure 50. Minimum momentum for positive charged particles in the east-west plane at the geomagnetic equator as a function of zenith angle.

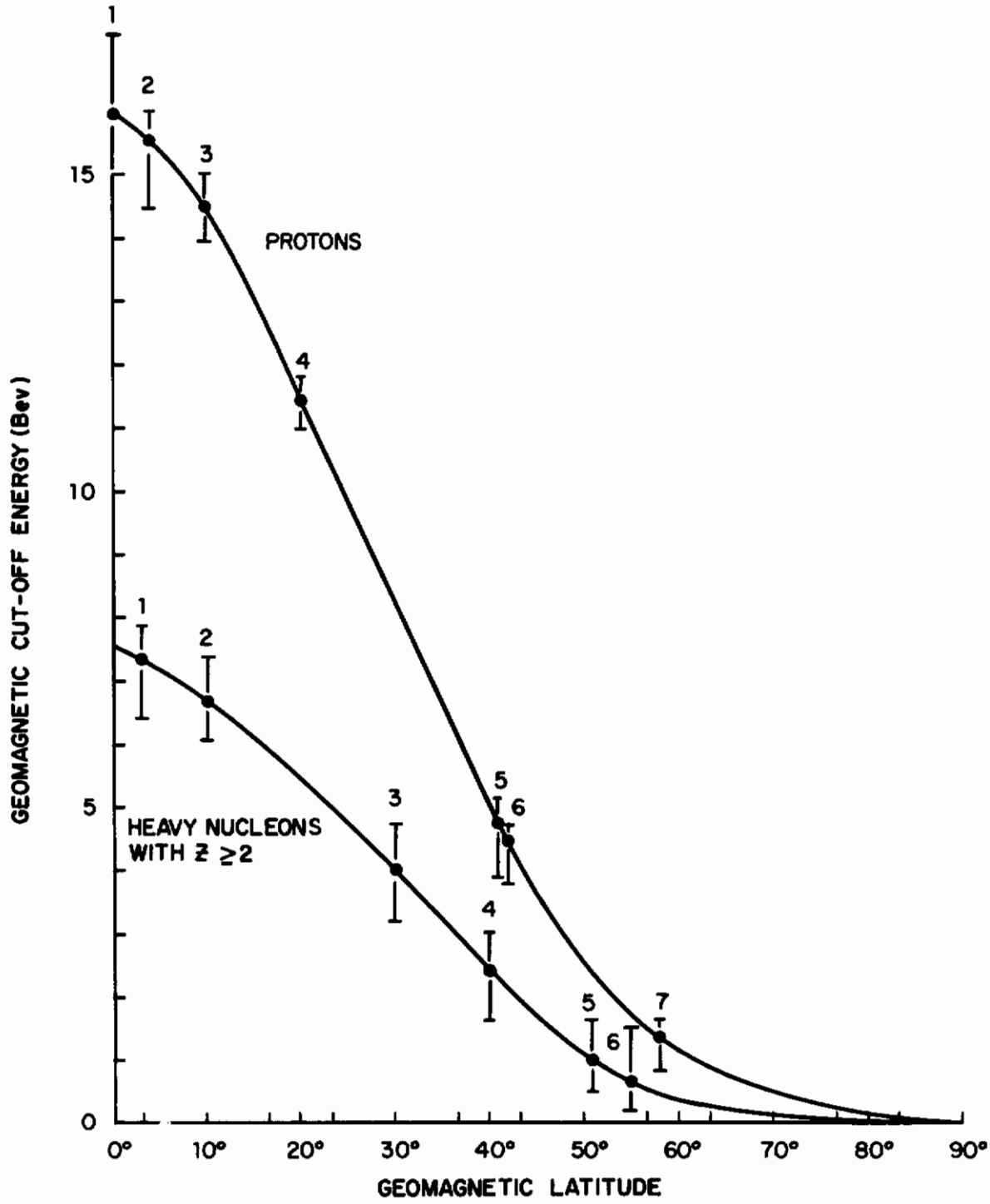


Figure 51. Dependence of geomagnetic cutoff energy for various primary cosmic ray constituents as a function of geomagnetic latitude.

The Geomagnetic Coordinate System

The energies of the primary cosmic ray particles that can reach the earth are a function of the magnetic latitude of the earth. The earth's surface field can be represented by a series of lines running north and south which intersect the centered dipole of the earth at geographic latitude $\Psi = 78^{\circ}\ 33'$ N and geographic longitude $\phi = 70^{\circ}$ W. This pattern of force lines establishes a set of geomagnetic coordinates (see Figure 52). Thus, for a given geographic latitude θ and geographic longitude Ω, the corresponding geomagnetic latitude λ is:

$$\arcsin\left[\cos\Psi\cos(\Omega-\phi)\cos\theta+\sin\Psi\sin\theta\right].$$

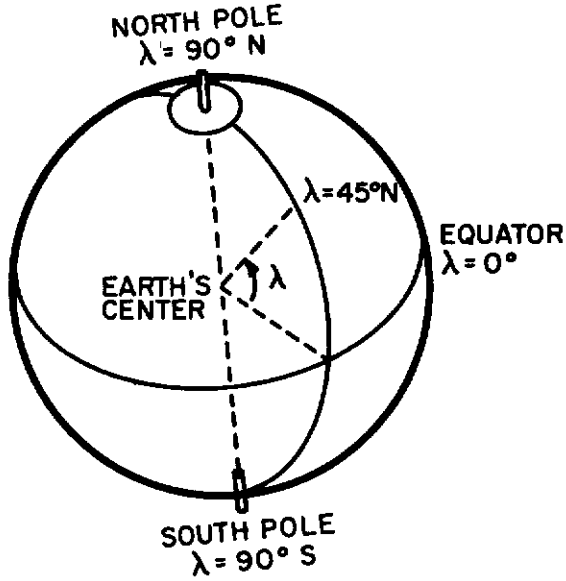
The corresponding geomagnetic longitude is:[66]

$$\frac{\arccos\left[\sin\Psi\cos(\Omega-\phi)\cos\theta-\cos\Psi\sin\theta\right]}{\cos\lambda}.$$

The geomagnetic equator does not coincide with the geographic equator, and the cosmic ray equator (the position where the cosmic ray intensity is at its lowest value) does not coincide with either the geomagnetic or geographic equators, as can be seen in Figure 53.[61] This effect is due to some magnetic effect associated with the earth and its field. This geomagnetic effect creates large variations of the primary cosmic ray intensity for different positions on the earth. These intensity variations are known as: (a) the geomagnetic latitude effect; and (b) the east-west effect.

The East-West Effect

For a given geomagnetic latitude, primary particles of certain intermediate energies can more easily penetrate the earth's magnetic field from the eastern or western direction depending upon the charge of the incident primary. This is known as the east-west effect. Since the primary cosmic radiation is composed predominantly of positively charged particles, intensity is greater in the western direction than in the eastern. As a positively charged particle approaches the earth at the equator, it is deflected toward the east, as is shown in Figure 54. In this figure, particle A+ has too little momentum ($M < M_c$) to reach the earth and is turned away from it by the magnetic field. Particle B+ has enough momentum ($M \geq M_c$) to reach the earth and must enter the atmosphere from the west, as is shown.[4] Figure 55 gives the minimum momentum for arrival of positively charged particles versus the geomagnetic latitude. The same phenomena apply to negatively charged particles, C-, but the direction is reversed; i.e., they will be deflected toward the west and a negatively



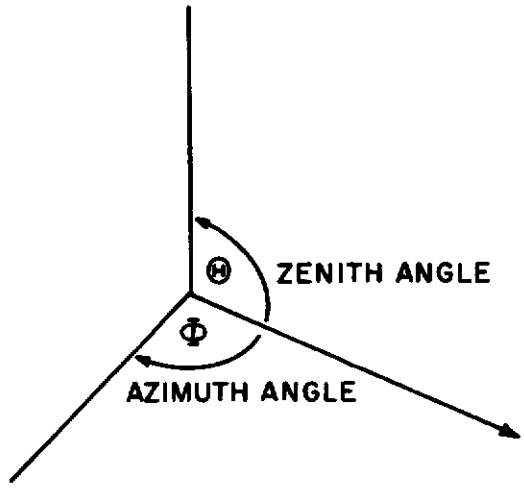


Figure 52. Arrangement of the geomagnetic coordinate system.

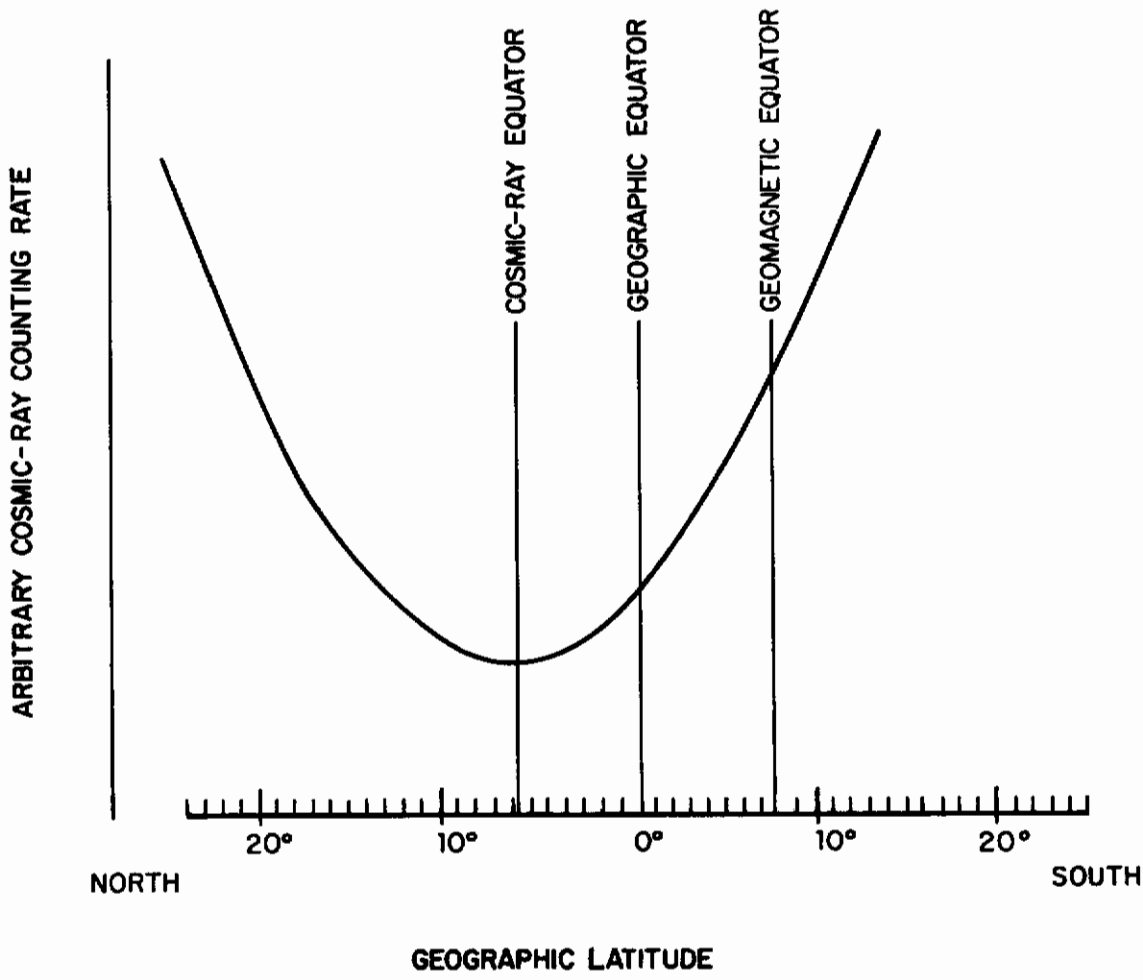


Figure 53. The position of the geographic, geomagnetic, and cosmic ray equators.

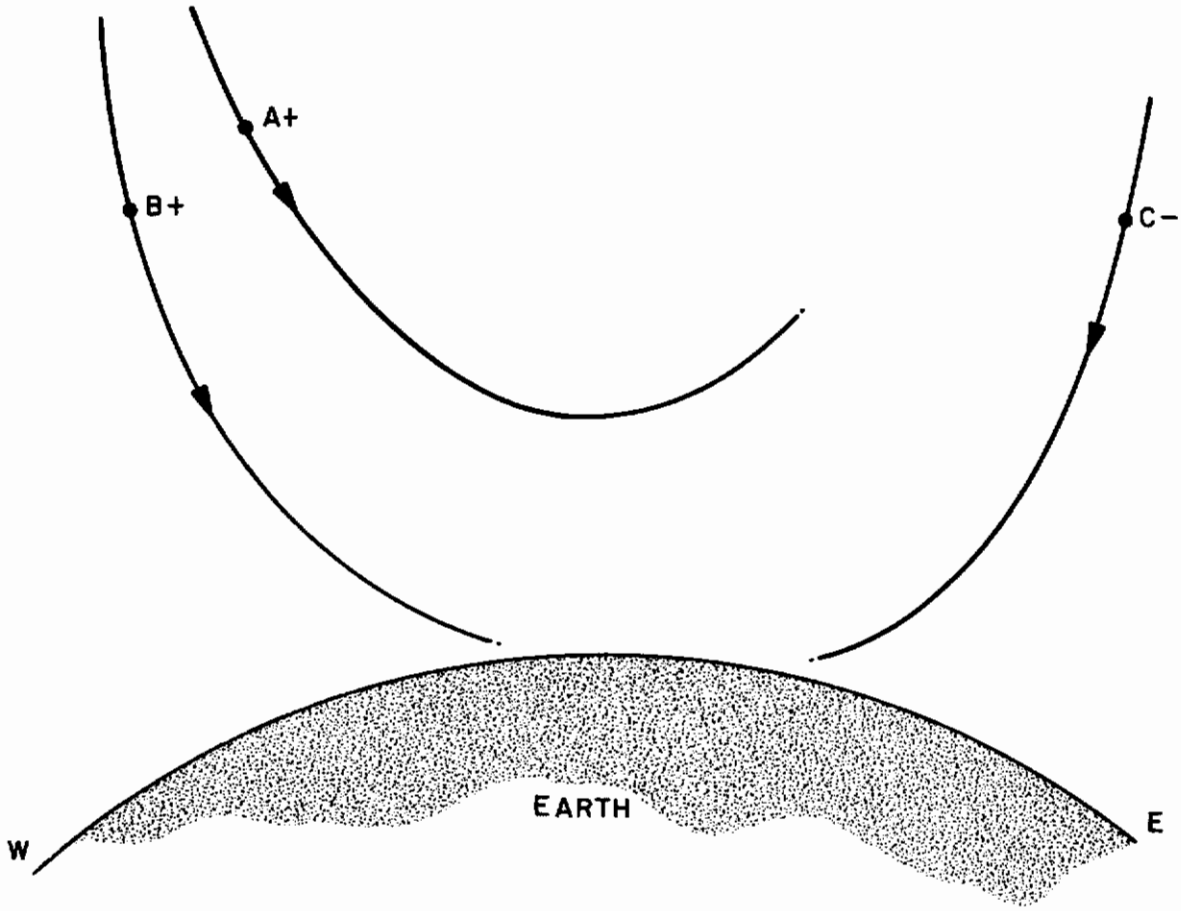


Figure 54. The east-west effect at the equator, looking north.

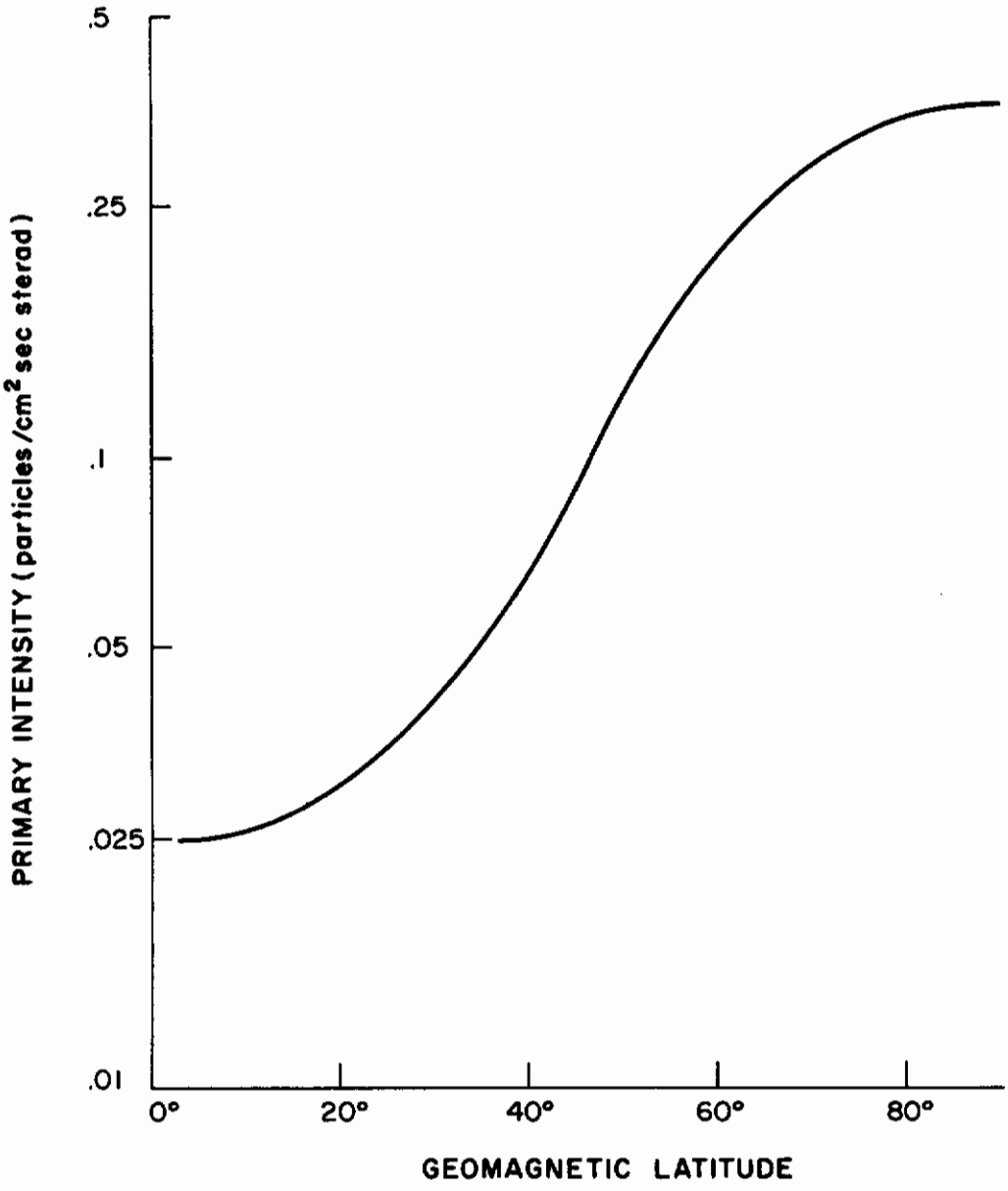


Figure 55. The geomagnetic latitude effect of the primary cosmic radiation. The figure shows clearly that, at low geomagnetic latitude, a great many of the primaries available outside the effective domain of the earth's field are not allowed to reach the top of the earth's atmosphere.

charged particle with low energy must enter the atmosphere from the east. The east-west effect is very small at sea level, but becomes increasingly significant at higher altitudes. It also increases with proximity to the geomagnetic equator.

The Geomagnetic Latitude Effect

This latitude effect is characterized by the fact that the total cosmic ray intensity increases from a minimum at the geomagnetic equator to a maximum at the geomagnetic poles. This effect is brought about by the variation y, the magnetic rigidity with geomagnetic latitude as previously discussed. Figure 55 shows the geomagnetic latitude effect of the primary cosmic rays.[25] As can be seen from the curve, the intensity rises steadily from 0° to ~55° geomagnetic latitude, above which it remains constant. This initial rise is caused, of course, by the geomagnetic cutoff effect. As the latitude increases, primary particles of lower energy are able to reach the earth's atmosphere. The fact that the curves of Figure 55 are essentially flat from $\lambda = 55°$ to the magnetic poles can be interpreted as due to the absence of primaries with energy below a certain critical value (about 0.6 Bev for protons). This lack of an observable increase in the cosmic ray flux at high latitudes gives rise to the so-called latitude cutoff "knee". Experiments have shown that the latitude knee is present only during periods of maximum solar activity but disappears during periods of minimum solar activity. Thus, it is affected by some solar-controlled mechanism. This phenomena will be discussed further in the section on the primary cosmic ray time variations.

Figure 56 shows the atmospheric pressure and depth as a function of altitude.

SECONDARY RADIATION

The extremely energetic primary nuclei of the galactic cosmic radiation strike against the top of the earth's atmosphere like heavy rain at an average rate of about one particle per square centimeter every second. Protecting the earth's surface and its inhabitants from this heavy bombardment is a layer of air over 1000 gm/cm^2 thick, equivalent to a protection of over 33 feet of water, between the earth's surface and outer space. In their travel through the atmosphere toward the surface of the earth, the incident primary cosmic rays interact with the nuclei of the air producing copious quantities of secondary particles. It is by this interaction process that the enormous energy of individual primary cosmic rays is dissipated in the protective air layer.

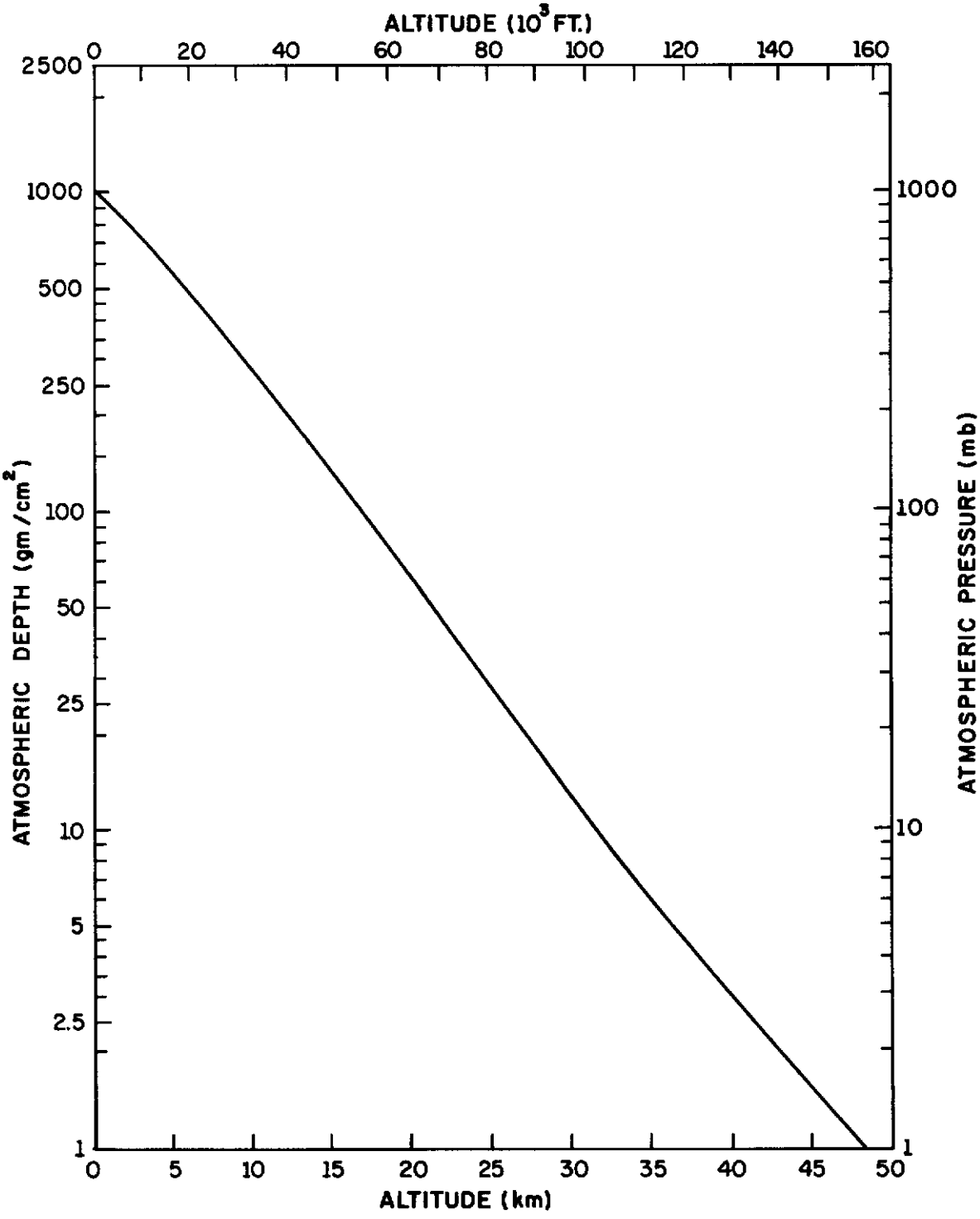


Figure 56. Atmospheric pressure and depth versus altitude. 1 atm. = 1013 mb = 1034 gm/cm^2; 1 ft. = 0.305 m.

The particles produced in the atmosphere as a result of this cosmic ray bombardment represent a complete catalogue of all particles known to physics.[55]

The nuclear components that make up the major part of the secondary radiation can be grouped into three general categories: (1) The nucleonic component, which includes the secondary produced protons and neutrons; (2) the electronic or soft component, which consists of electrons and gamma rays; and (3) the mesonic or hard component, which includes primary μ mesons.

In addition to this secondary cosmic radiation produced by high energy primary interactions, there exists in the atmosphere the products of transformation of air nuclei which have been involved in high energy primary collisions. They include various stable and radioactive nuclei of nitrogen, oxygen, carbon, argon, neon, xenon, and krypton. Although these particles occur in the atmosphere, most are quite rare and represent only a minor part of the total particle cascade initiated by the primary nuclei.

The most important particles in the cosmic radiation, apart from the primaries, are the secondary nucleons, or the nucleonic component (proton and neutron) and the tertiary component consisting mainly of μ mesons, gamma rays, and electrons.

Some of the possible cosmic ray reactions by which the energy of the primary nuclei may be expended to the product particles of the atmospheric nuclei interaction are shown in Figure 57. As can be seen from the figure, the violent "stars" produced when the primary particles destroy air nuclei consist chiefly of many mesons, protons, neutrons, electrons, and photons as well as many different fragments of the original nucleus. These various particles in the star eventually produce electron cascades or bremsstrahlung radiation, nuclear cascades, μ mesons, as well as other smaller stars. Gradually, then, by this process the incident energy of the primary nuclei is used up in the multiplicity reaction or "air shower" as depicted in the diagram.

Roughly speaking, then, Figure 58 shows that the nucleonic component predominates in the uppermost 5 percent of the atmosphere; electrons, positrons, and gamma rays, as the electronic component, predominate in the pressure region between 100 to 600 gm/cm^2 (5 to 17 km); and the μ mesons component predominates in the lower region as well as below the surface of the earth.[50, 60] This distribution is a consequence of the properties of the particles produced in the initial high energy collision.

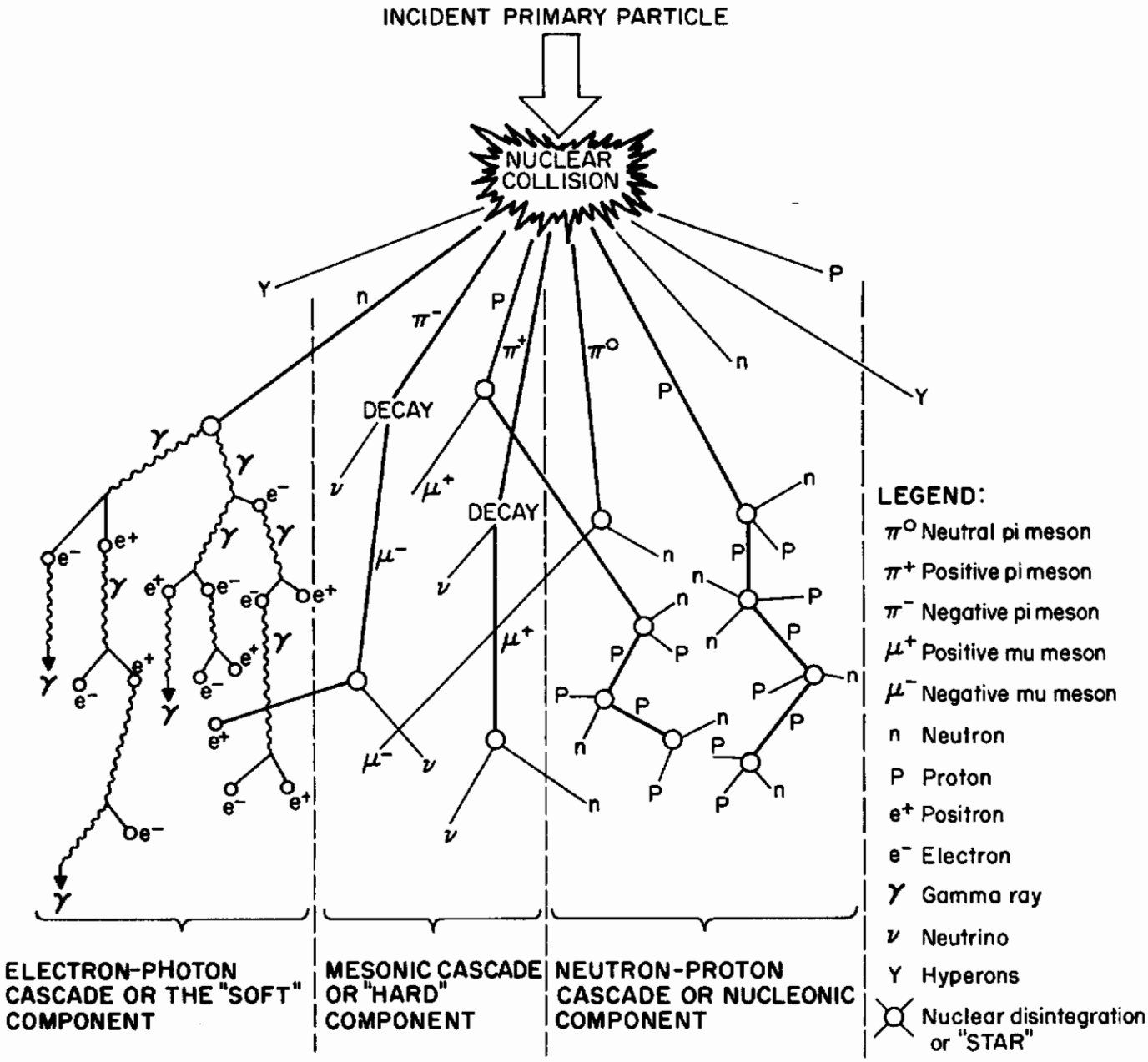


Figure 57. Genetics of cosmic radiation within the atmosphere.

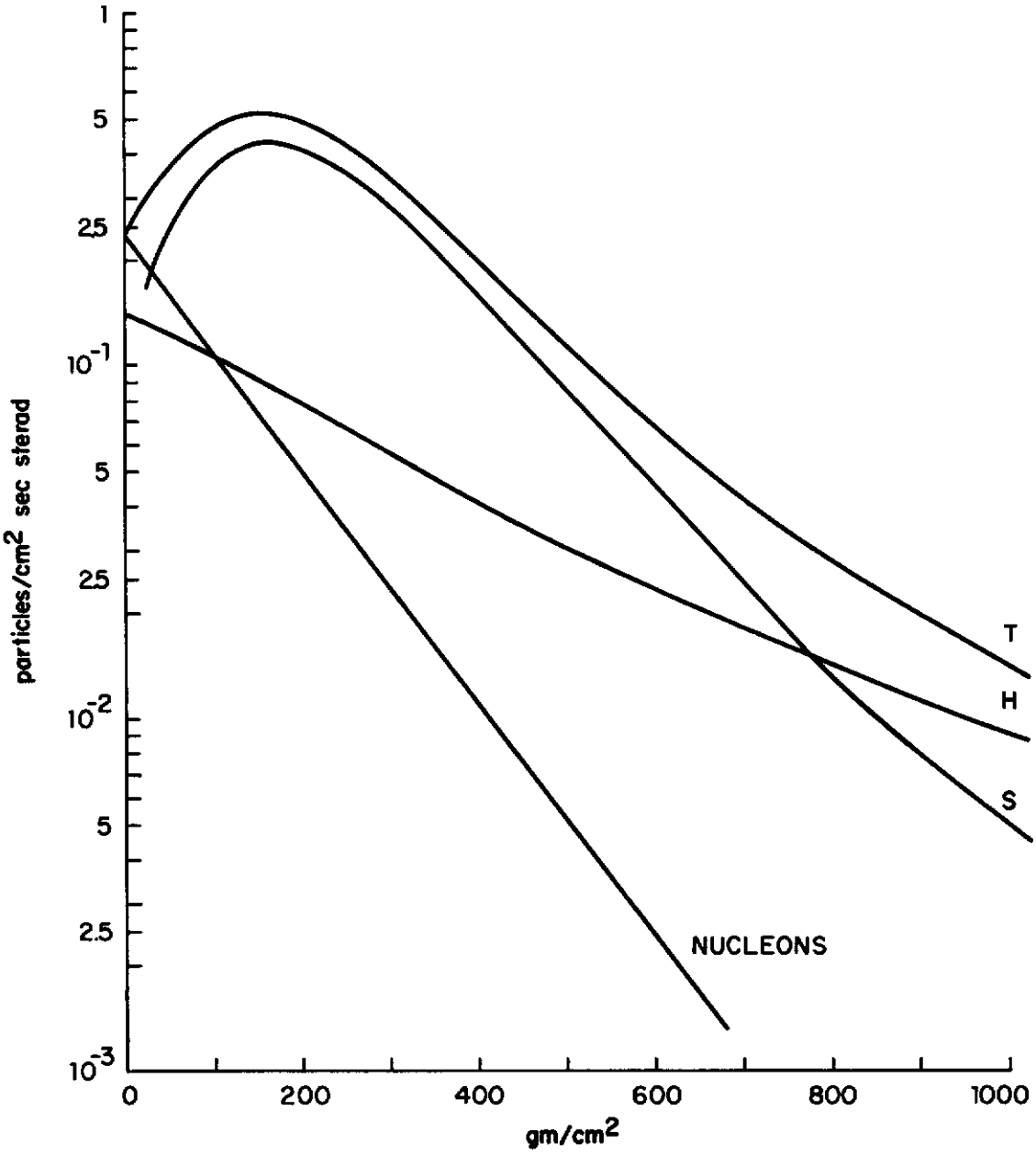


Figure 58. Intensity of the various components of the secondary cosmic radiation in the atmosphere as a function of atmospheric depth for geomagnetic latitudes greater than 50°.

The μ mesons can pass relatively freely through nuclear matter. They lose energy to the surrounding air by weak electronic excitation with comparatively small energy loss. As a result, μ mesons predominate in the secondary cosmic radiation at great atmospheric depths, and are the most penetrating component of this radiation. Hence, they are designated as the "hard component" of cosmic radiation. Figure 59 depicts the flux of the μ mesons in the atmosphere and Figure 60 shows their energy spectrum.*

The energy of the incident primaries is given up to the products of collision which in turn lose their energy through the production of electron-photon cascades. As the primaries and product particles penetrate deeper into the atmosphere the electron-photon cascades increase rapidly. As a result, this process is responsible for the strong maximum in the secondary cosmic radiation at an average atmospheric depth of about 150 gm/cm^2 or about 14 km. As shown in Figure 61, the electronic component represents the strongest contribution of the secondary radiation and is known as the "soft component" of the cosmic radiation.* Figure 62 depicts the integral and differential spectra of the soft component.

Arbitrarily, Rossi[60] defines the hard component of the secondary cosmic radiation in the atmosphere as that portion able to penetrate 167 gm/cm^2, or an equivalent thickness of 15 cm of lead shielding. The soft component is defined as that portion which can penetrate 5 gm/cm^2, or about 0.5 cm of brass minus the hard component. Roughly speaking, the hard component consists mainly of highly energetic μ mesons and possibly a very small number of residual fast protons and neutrons. The soft component, on the other hand, is made up essentially of positrons and electrons and about an equal number of photons. All of these components have energies of less than 200 Mev. The photons in this soft component are a result of bremsstrahlung. It must be emphasized that the words "hard" and "soft" are used very loosely; they only indicate roughly the penetrating power of the various components of the secondary cosmic radiation.

In addition to the above components, there are also come secondary protons and neutrons produced as a result of primary interactions which are fragments of the original "knock-on" nuclei. These produce further nuclear reactions of smaller energy, resulting in still more nuclear cascades.** Figure 63 shows the neutron counting rate as a function of geomagnetic latitude.[69] The low energy protons lose energy

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* See reference nos. 23, 25, and 50.

* See reference nos. 7, 10, 50, and 66.

** See reference nos. 13, 46, and 55.

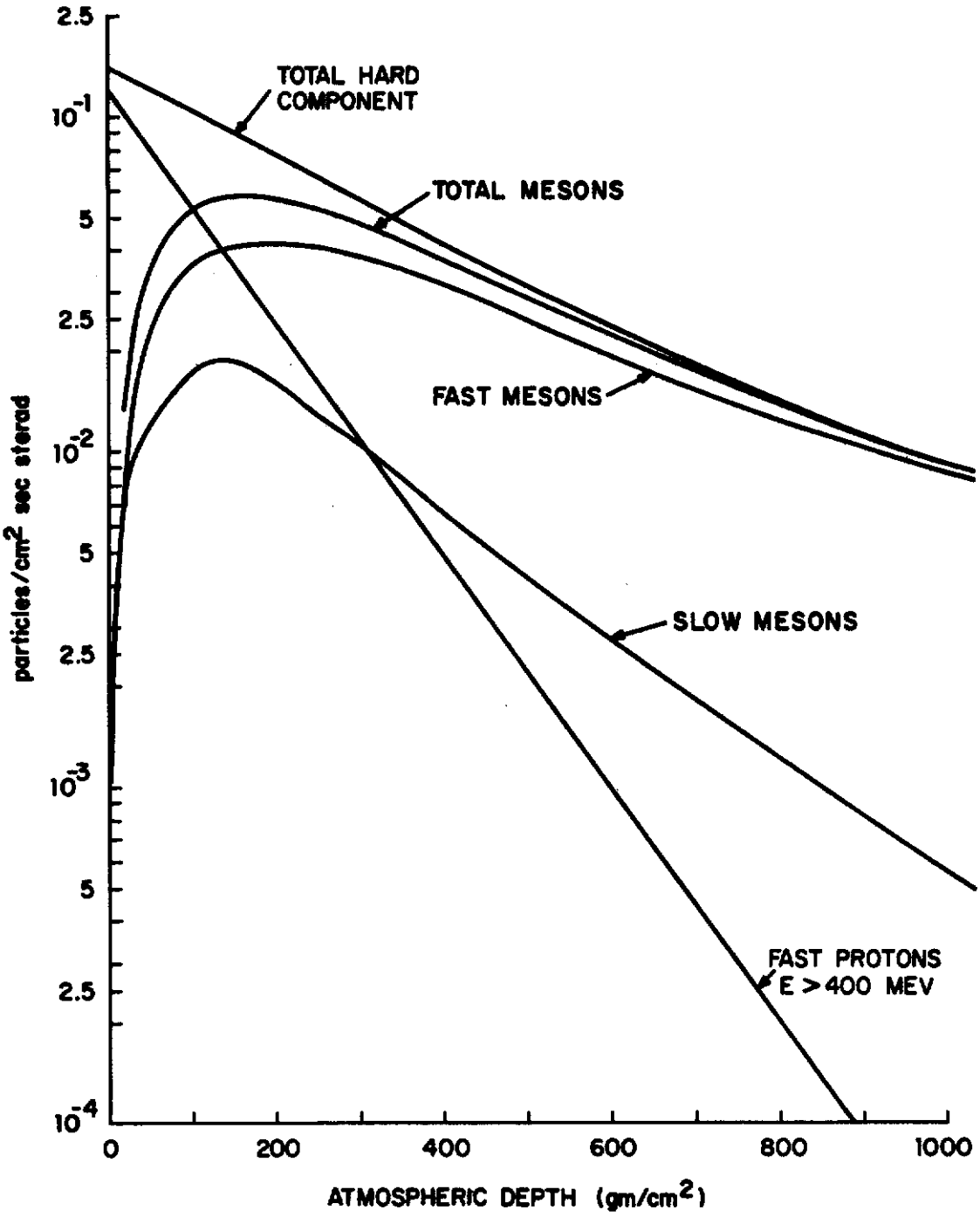

Figure 59. The flux of the hard component of the cosmic radiation as a function of atmospheric depth.

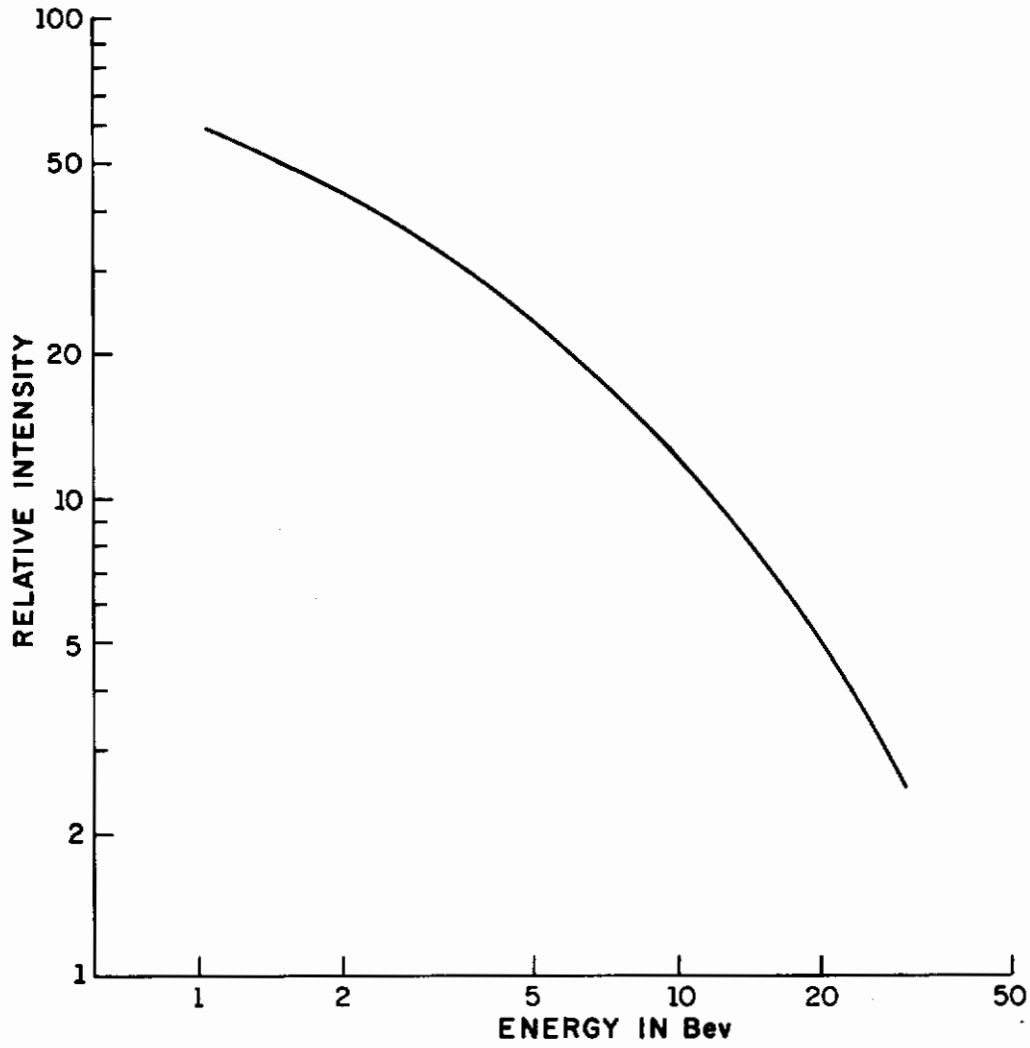

Figure 60. μ-meson energy spectra (American Review of Nuclear Science, Vol. 10, 1960).

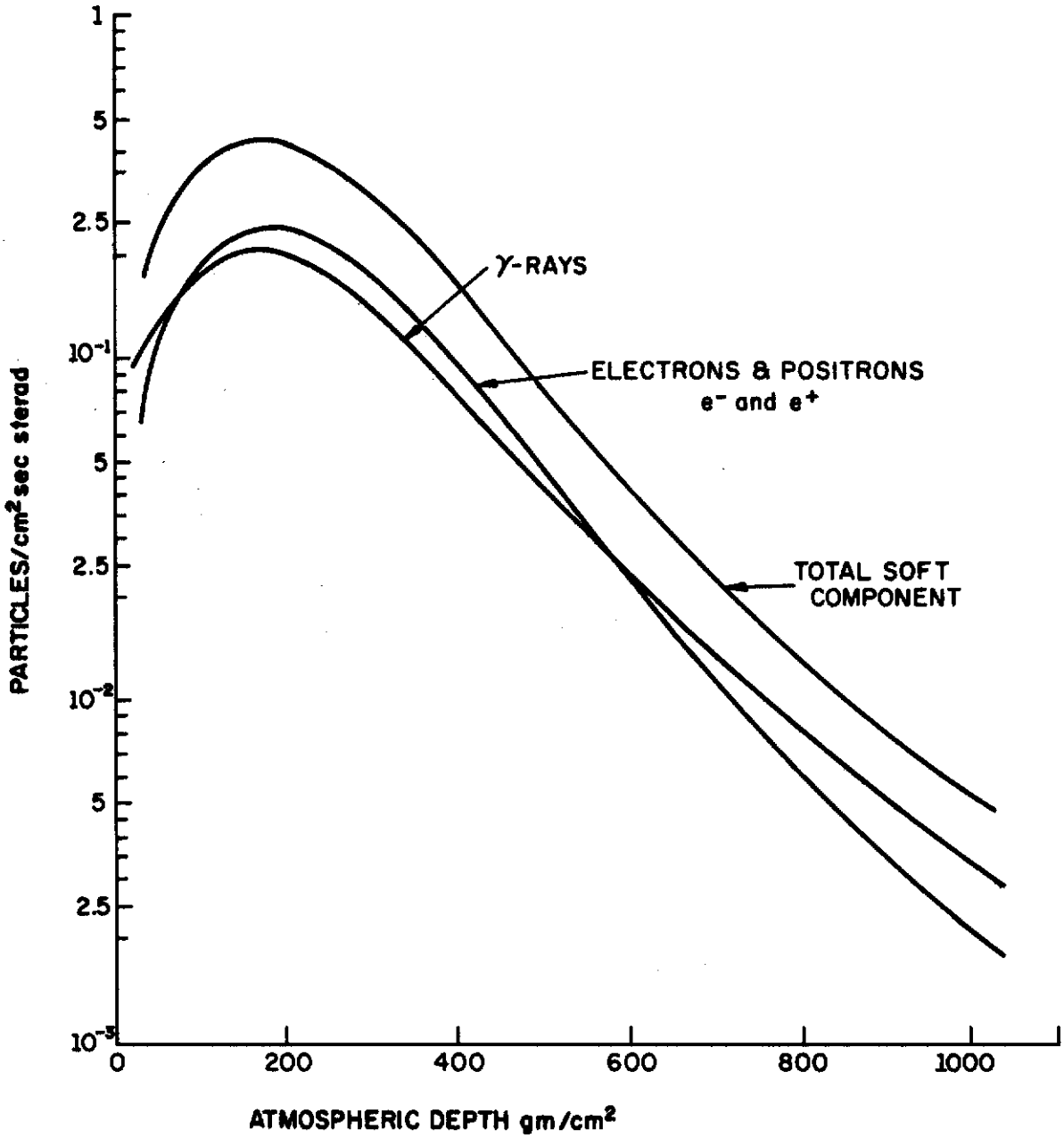

Figure 61. The flux of the soft component of the cosmic radiation as a function of atmospheric depth.

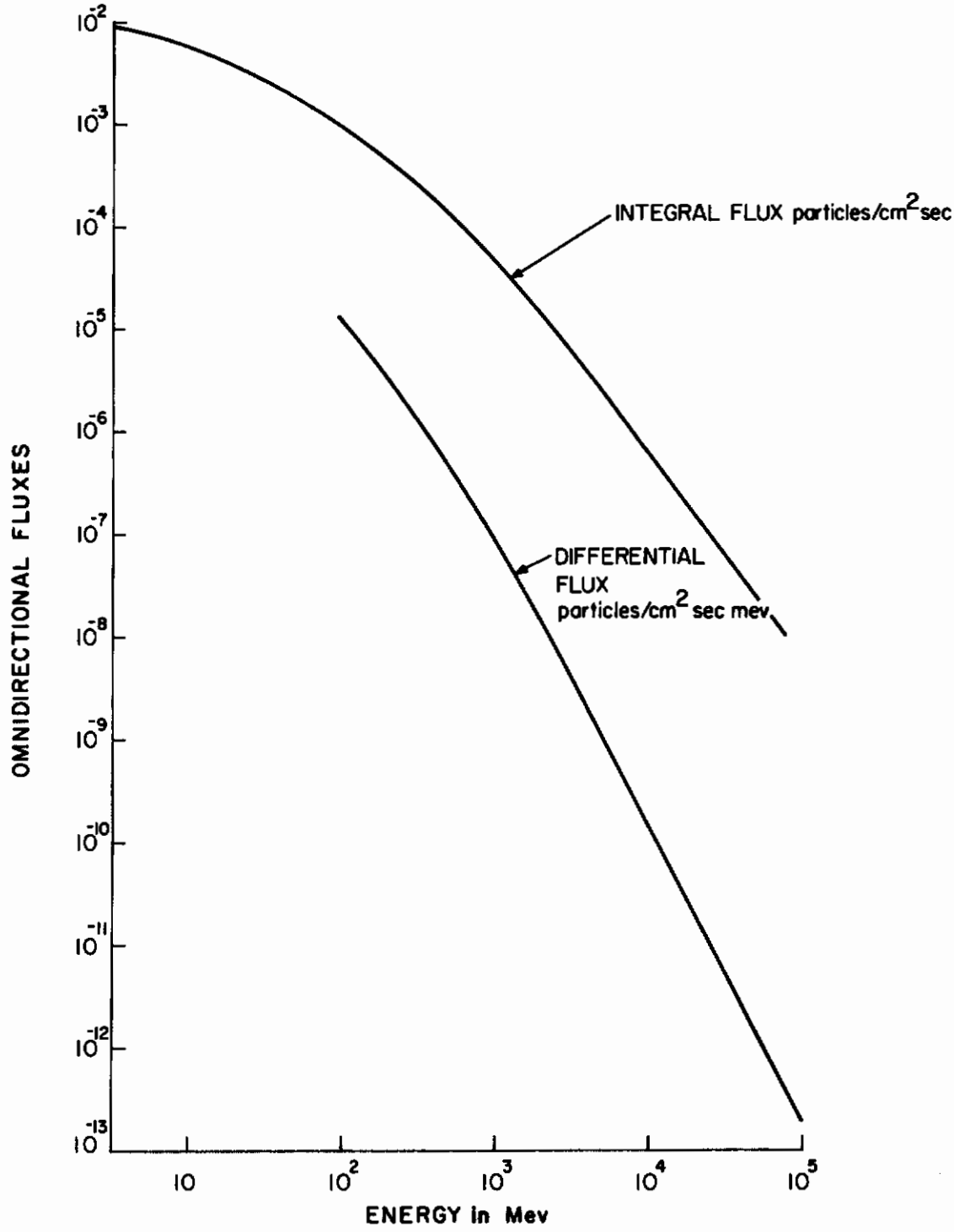

Figure 62. The differential and integral energy spectrum of the soft component at sea level.

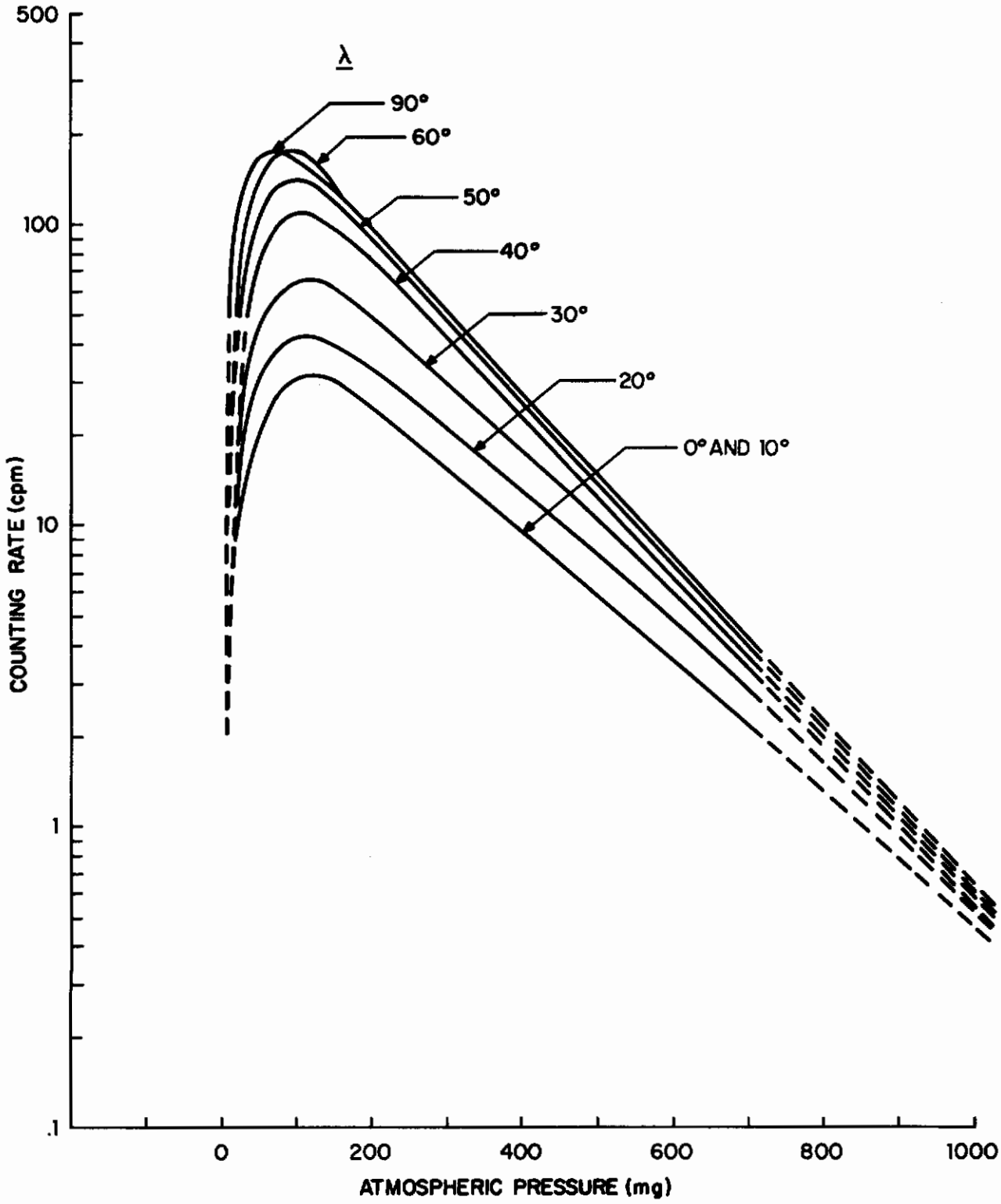

Figure 63. Neutron counting rate as a function of atmospheric pressure for various geomagnetic latitudes.

rapidly by ionization and the neutrons are captured upon thermalization by nitrogen-14 forming radiocarbon.[30] Figure 64 shows the number of neutrons captured in the atmosphere by producing C^{14}. These nuclear interactions are but a few of the complicated processes that are continually going on in our atmosphere. Figure 65 shows the neutron energy spectrum for various altitudes above the earth's surface.[30]

Thus, as a primary nucleus enters the top of the earth's atmosphere, it will undergo a number of collisions with the air nuclei, producing a cascade of electrons, photons, μ mesons, and nucleons which shower the lower atmosphere of the earth and its surface.

Atmospheric Neutrons

Cosmic ray neutrons are secondary particles produced in the atmosphere as a result of primary charged particle collisions with atmospheric nuclei. There are few, if any, primary neutrons reaching the earth from space due to their short half-life. Neutrons are produced in the atmosphere with all energies from those of primary cosmic rays to thermal neutrons. At atmospheric pressures ranging from 200 to 600 mb, equilibrium is established between neutron production and absorption. This region is known as the "equilibrium region of the atmosphere".

About 17 percent of the neutrons are created at high enough altitudes that they "leak out" the top of the atmosphere. Figure 66 shows the neutron count rate as obtained by Hess[31] as a function of altitude. The peak at 20 km is due to neutrons in the earth's atmosphere. The increase in the counting rate at 1000 km is due to the rocket passing into the inner Van Allen belt. These outward escaping neutrons eventually undergo a natural free decay to form protons. Others will interact with nitrogen atoms at the top of the atmosphere producing Carbon^{14}, releasing protons. Many of these protons from the $N^{14}(n, p)C^{14}$ reaction eventually become trapped in the earth's magnetic field and, hence, contribute to the formation of the inner Van Allen radiation belt.

The Altitude and Geomagnetic Latitude Effects

Figure 67 reveals a number of interesting points: The total secondary cosmic ray intensity increases with increasing altitude (decreasing pressure); but at high altitudes (in excess of 50,000 feet) the intensity starts to fall off with increasing height. In addition, the intensity at any pressure is seen to increase with increasing geomagnetic latitude. This behavior may be explained in the following manner: The secondaries account for the small rise in the observed intensity at high altitudes. As they pass down through the atmosphere they are slowed down and/or

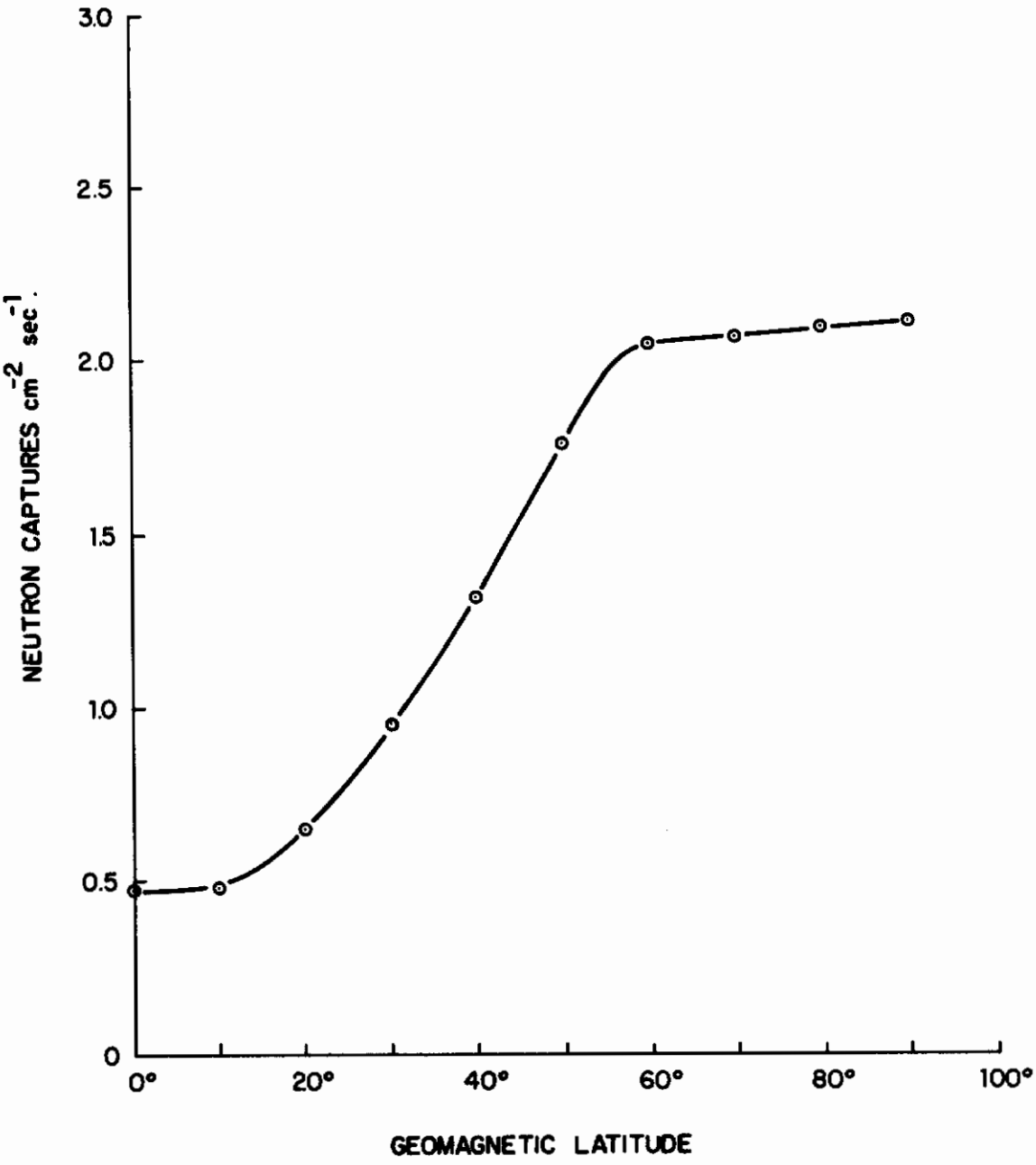

Figure 64. The total number of neutrons cm^{-2} sec^{-1} of energy less than 0.5 Mev absorbed in the earth's atmosphere by the $N^{14}(n, p)C^{14}$ reaction. This should be at least a lower limit to the total number of neutrons cm^{-2} sec^{-1} produced in the earth's atmosphere.

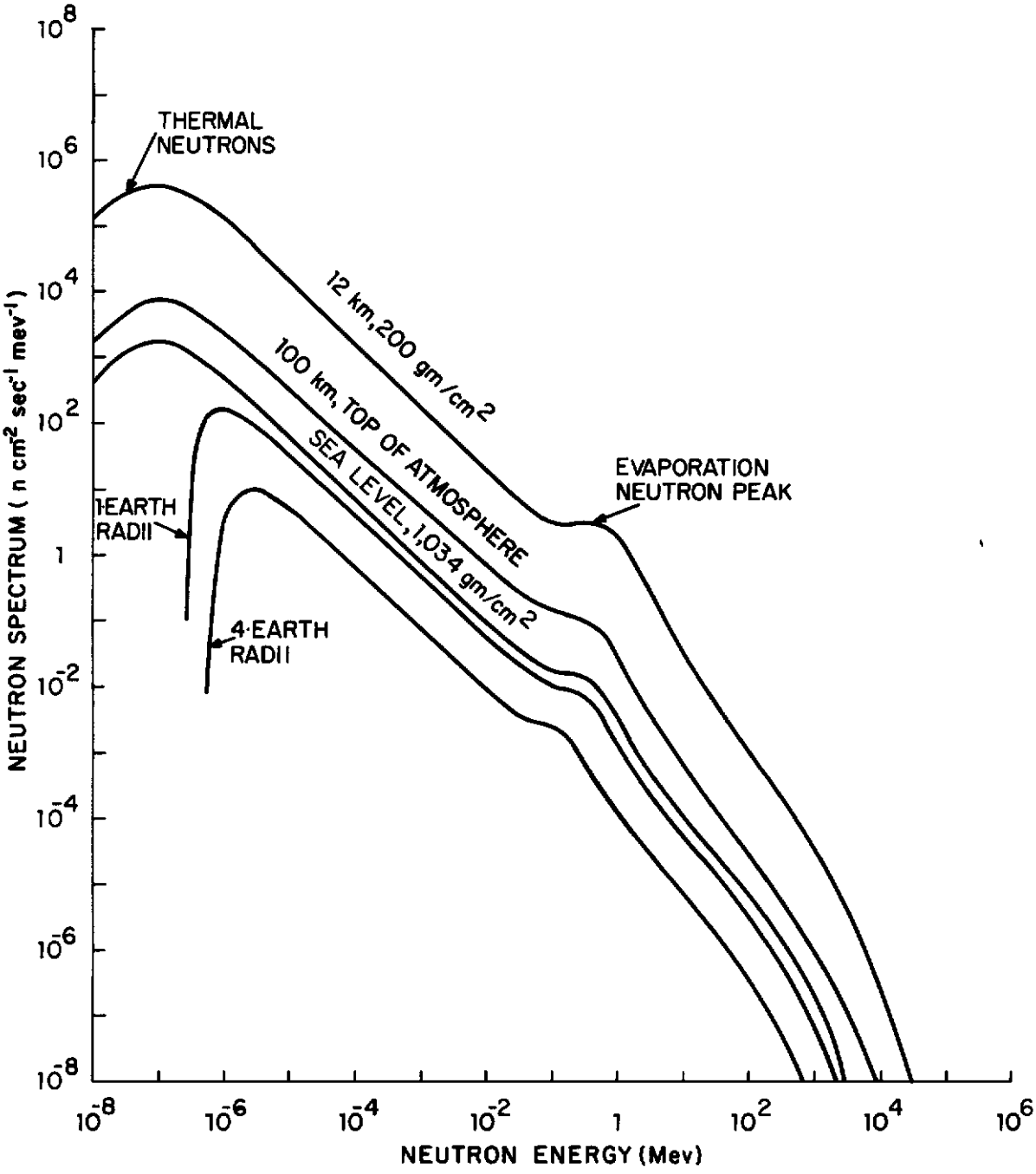

Figure 65. The cosmic-ray neutron energy spectrum as a function of altitude above the earth's surface (accuracy ±25%).

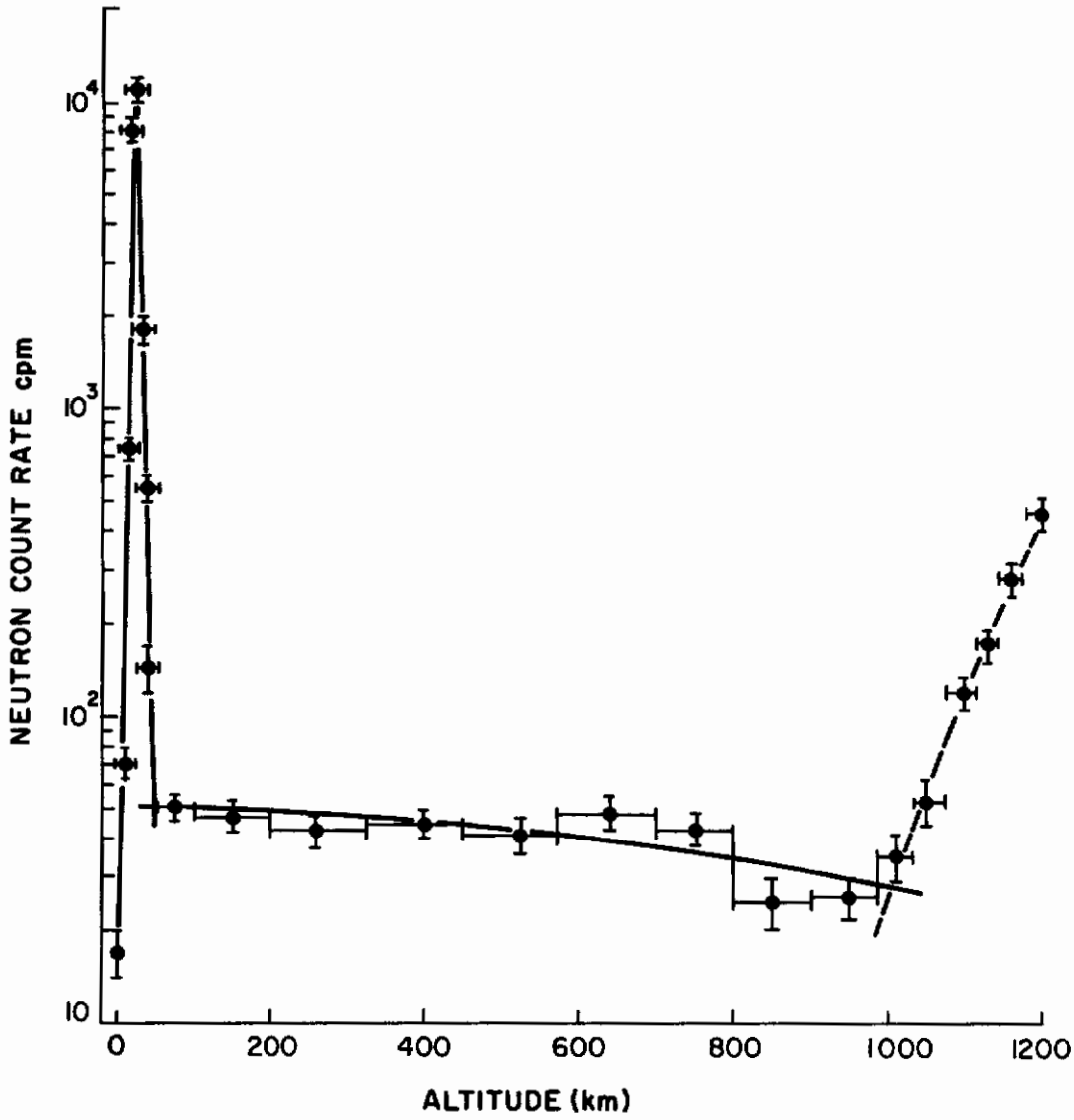

Figure 66. The neutron count rate as a function of altitude above the earth's surface.

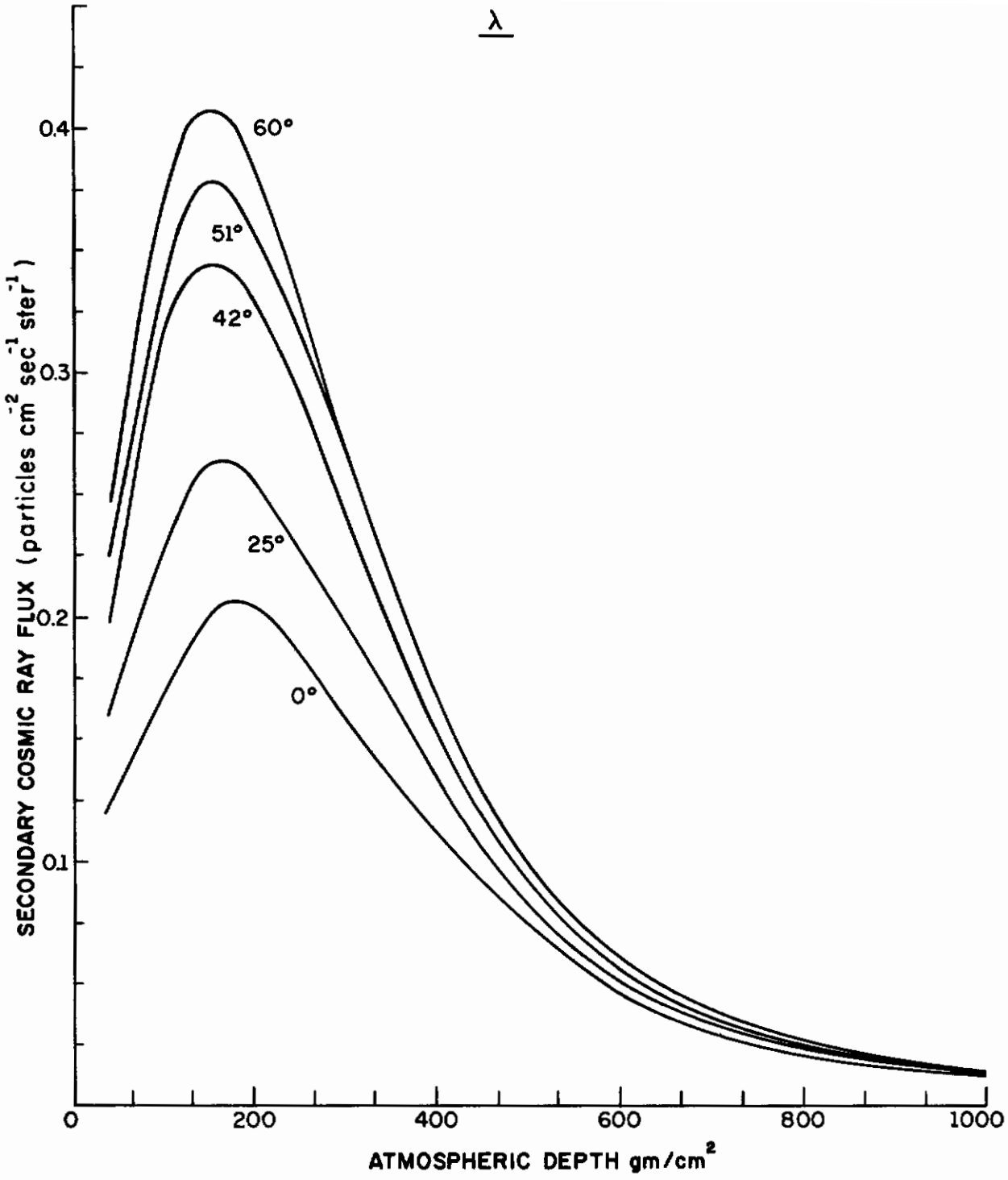

Figure 67. The secondary cosmic-ray flux as a function of atmospheric depth for various geomagnetic latitudes.

absorbed, producing less ionization. This causes the intensity decrease as the atmospheric pressure increases.[22]

The geomagnetic latitude effect (see Figure 68)[50] can be explained by the fact that the nuclear cascades are dependent on the flux of primaries that interact at the top of the atmosphere, and since the primary radiation is a function of geomagnetic latitude then, also, the secondary radiation will be latitude dependent. The latitude effect, i.e., the change in radiation intensity from the magnetic equator to the poles, is about 10 percent at sea level; but increases with increasing altitude to a value of about 90 percent at the top of the atmosphere. Thus, nearly ten times as many primary particles from space reach the earth's atmosphere at 50° geomagnetic latitude as at the equator. This accounts for the change in intensity with geomagnetic latitude.[22]

The radiation dose rate in the atmosphere due to secondary cosmic radiation is shown in Figures 33 through 37 of the main section and the dose rate due to neutrons is shown in Figure 69. Figure 70 shows the neutron dose rate in space as a function of geomagnetic latitude.[76] Figure 71 shows the ionization in the atmosphere as a function of radiation dose rate.

Cosmic Radiation with Regard to Other Planets

As a sidelight, it would be interesting to determine an order of magnitude value of the average background of the surfaces of the most interesting planets (from the standpoint of space exploration), Mars, Venus, and the moon. The planet Venus is essentially the same size as the earth and many feel that it has a similar magnetic field. Since it does possess an atmosphere, it is likely to have a similar cosmic ray background as that of the earth. The moon has a negligible atmosphere and a weak magnetic field. As a consequence, its cosmic ray background should be that of free space, namely 1.9 mr/hr at solar minimum and 0.6 mr/hr at solar maximum. In addition, it will be subjected to all of the dangerous radiations associated with solar flares. Mars, on the other hand, has approximately 8.5 percent of the atmosphere of the earth with about 1/10 of the magnetic field. As a result, its natural background radiation is expected to be much higher than that of the earth, or approximately an average value of 0.65 mr/hr, while that at the earth's surface is about 0.014 mr/hr, or about 45 times as much as that on earth. In addition, its small atmosphere will not afford as much protection against the dangerous solar flare radiation as the earth's atmosphere.

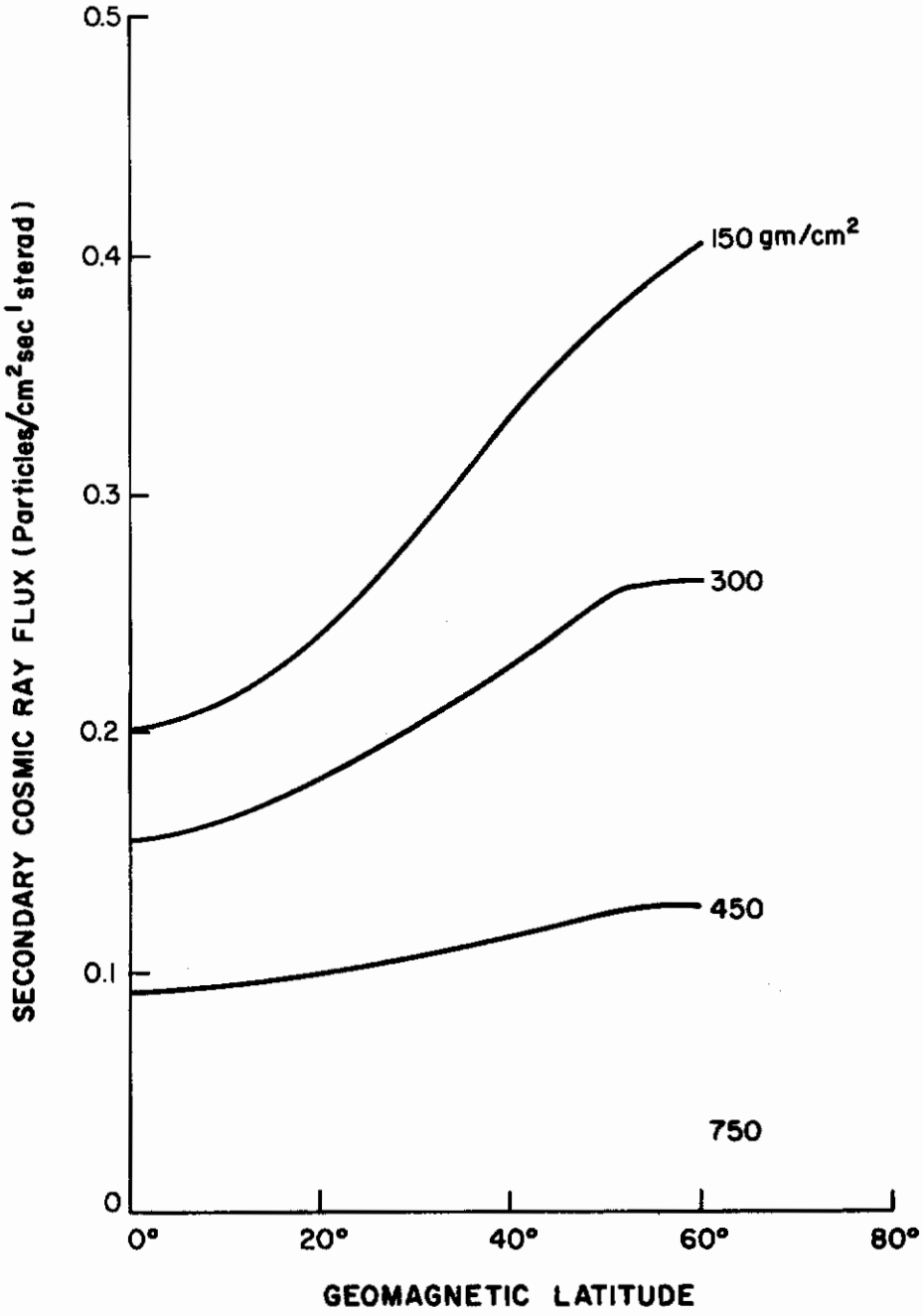

Figure 68. The secondary cosmic-ray flux as a function of geomagnetic latitude for various atmospheric depths.

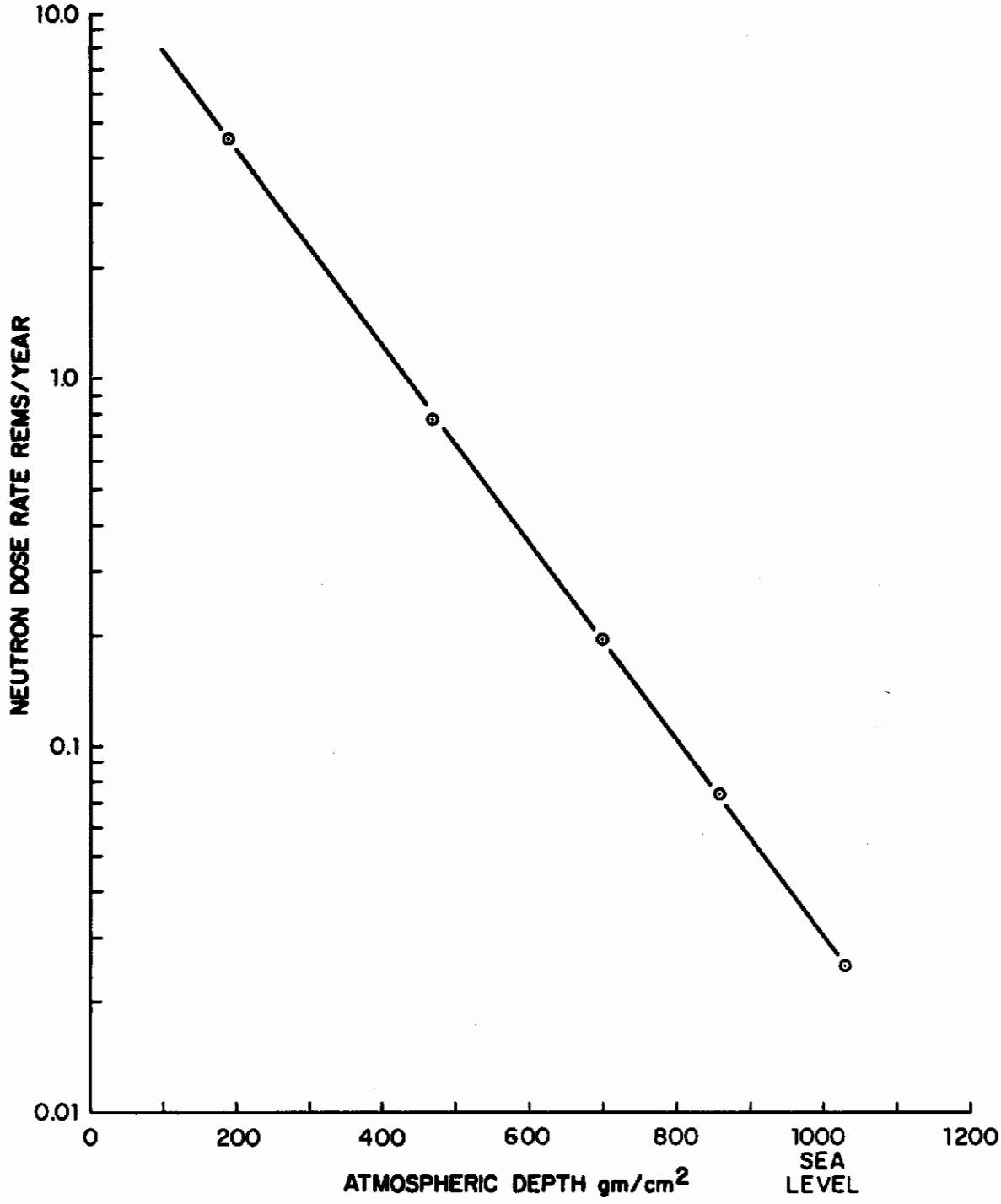

Figure 69. The neutron biological dose rate as a function of atmospheric depth at $\lambda = 44^{o}$.

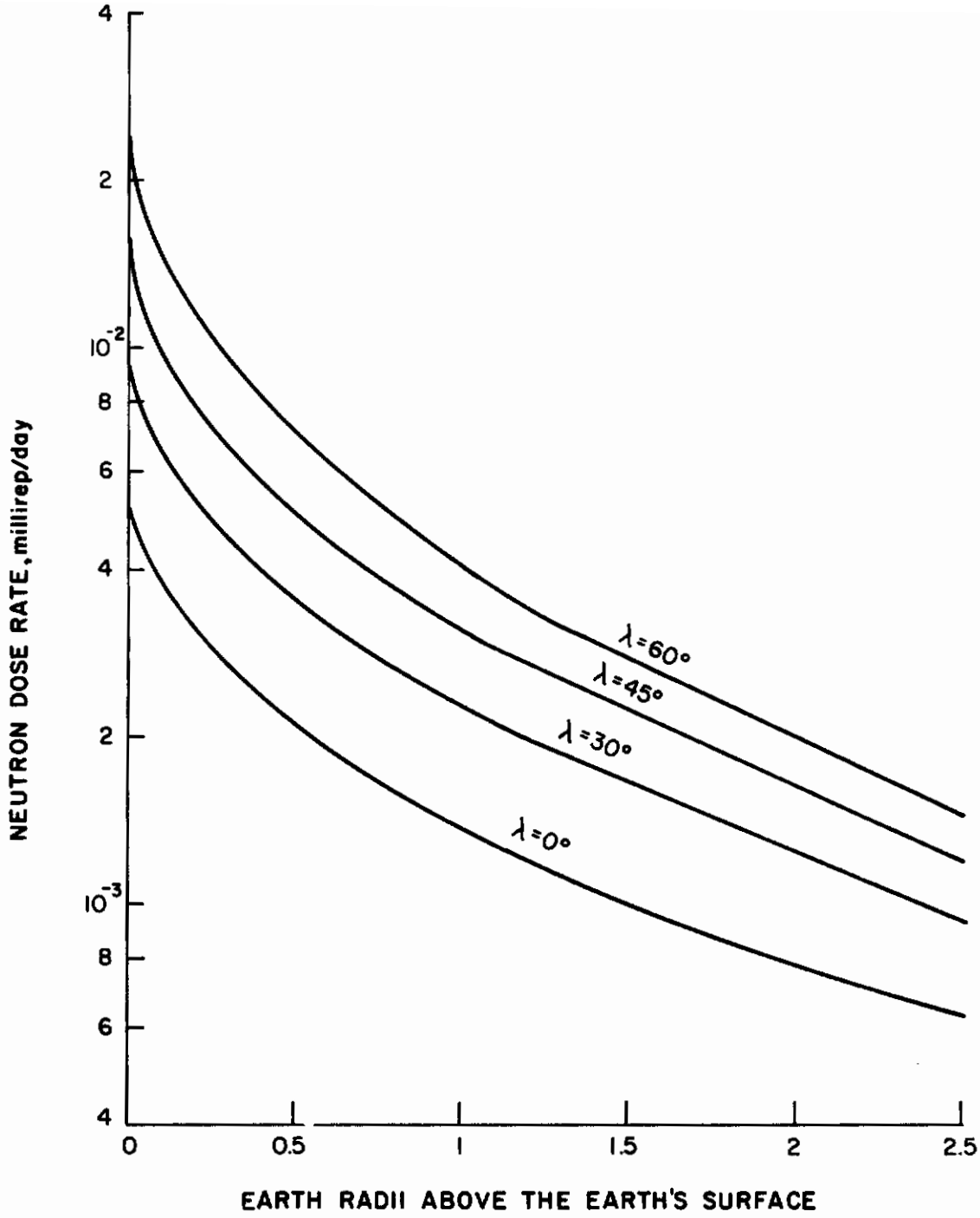

Figure 70. The dose rate due to neutrons which are produced in the atmosphere and which diffuse into space.

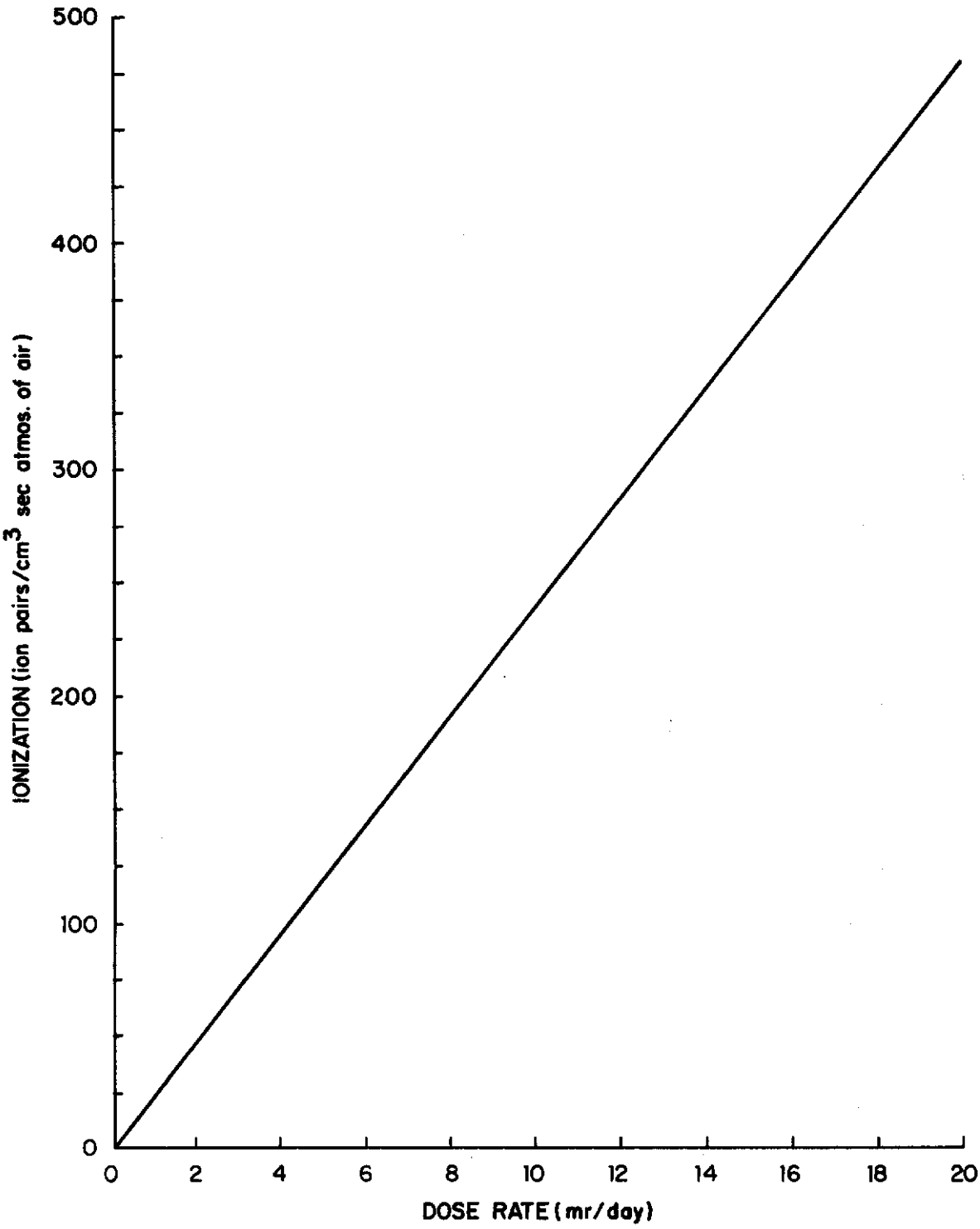

Figure 71. The ionization in the atmosphere as a function of radiation dose rate.

SECTION IV

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SECTION V

BIOLOGICAL EFFECTS OF SPACE RADIATIONS

In the preceding sections describing the categories of existing radiations in space, information was given on the spectra which man will encounter and in some cases theoretical doses were described. It is the purpose of this chapter to delineate the effects of these radiations on man in space.

It would be inappropriate in this space-oriented guide to present a thorough discourse on the biological effects of ionizing radiations. This is especially so in light of the vast literature which has been written on the subject and which is generally available. Hence, only a very brief treatment of general biological interactions is included as an introduction to the effects of space radiations. Actually, there is nothing mysterious about these particular effects. We are not completely certain at this time of the way ultra-high energy galactic cosmic ray particles affect biological matter, but these are of such low intensity that they are not considered a cause for acute concern, except for the caveat issued by some that certain sensitive body organs, such as the hypothalamus may be damaged by the concentrated energy deposition characteristic of these particles. As for the other radiations in space, the solar radiations, Van Allen particles, and low energy components of the cosmic ray beam, their behavior is the same as their counterparts of man-made origin, and consequently their effects may be compared to experiments and tests performed in the laboratory. For example, protons of a given energy will interact with matter in precisely the same manner regardless of whether they are from a solar flare or a cyclotron.

Concern over the hazards of naturally occurring radiations in space has arisen only in the last few years. The danger potential was not recognized even as short a time ago as 1949. Though it appears humorous now, viewed in light of our new knowledge, the following quotation from the Journal of Aviation Medicine of that year illustrates the changing emphasis: "...Whereas the various kinds of radiations prevailing in space hardly will be harmful to the passengers of a space ship..."[1] Times have changed.

Ready answers are not available to such questions as: "What will happen to a man if caught in a solar flare proton beam?" or "What are the genetic and life-span shortening effects of long-term exposure to cosmic rays?" The radiobiologist often must appear to be equivocating when he couches his replies to such questions with vagueness: that a particular

type of radiation affects different parts of the body in different ways; that radiations of different types may affect a particular organ in different ways; that sensitivity varies considerably from individual to individual; and, probably the most unsatisfying answer of all, that in many cases it cannot be determined whether a particular dose should be considered "harmful". When these biological uncertainties are considered along with the vagaries of space radiation, it is small wonder that questions of the above kind go begging for direct answers.

In the case of genetic damage, i.e., the increased probability of producing mutants, nearly all authorities are in agreement that there is no lower threshold below which no hazard exists. That is to say, any amount of ionizing radiation is deleterious in this respect, though the increased probability of producing defective mutations may be very slight indeed for small doses. There is a distinct likelihood that the problem of genetic damage will be minimized, at least in the initial stages of space exploration, by judicious selection of "astronauts"--picking men who do not desire to procreate further. In any case, the effect on the general population will be slight due to the exceedingly small percentage of the populace which will be exposed. The philosophical implications of such planning are inappropriate in this guide and are omitted entirely.

In discussing the other type of biological response to radiation, somatic damage, we are on firmer ground. Radiation health physics is an established field and much knowledge of the cause-effect relationship between radiation and man has accumulated. Still, however, the degree of assurance we have that a particular dose will be harmful or not is a relative quantity because, for one thing, radiation effects are closely associated with statistical probabilities, and, for another, there is a diversity of opinion on what constitutes harm. Obviously, some individuals are more willing to accept risk than others, and some are more willing to accept a measure of inevitable damage than others.

ABSORPTION OF IONIZING RADIATION

Generally speaking, radiation causes the greatest damage to living matter through an indirect sequence of events. As radiation penetrates tissues, energy is given up to molecules in its path. This absorption results in electronically excited and ionized molecules in the "target" tissues. These molecules in turn undergo secondary reactions either in collisions or spontaneously, and ultimately come to a stable condition. At this point, with the resulting rearrangement of molecular structure, physical damage from the energy deposited has terminated; the products are in thermal equilibrium, and damage is limited to those molecules which suffered collision. But these rearranged molecules are not in chemical equilibrium;

they then further react chemically with each other and with their surrounding molecules to produce chemical changes. Finally, in living matter, these chemical changes cause a biological response in affected tissues. That is, abnormal molecules replace and interfere with essential normal ones.

Though the preceding sections have shown that not all radiations harmful to man are found in consequential amounts in space, i.e., neutrons and x-rays are practically absent, we cannot dismiss any type of radiation from an analysis of dose to occupants of space vehicles because of the profusion of particles and bremsstrahlung which are created as secondary radiation within the vehicle walls. The mechanism of energy exchange from the incident primary and secondary radiations to tissues is summarily given below; the reader is referred to standard texts for more thorough discussions of these basic interactions.

Protons and Heavy Ions

As with other types of radiation, the modes by which protons and heavier positive ions expend their energy in matter are dependent on numerous factors, the principal ones being their energy and charge. Because of their electrical charge, these particles exert forces on the electrons and nuclei of atoms and molecules along their paths in tissue. These forces cause electrons to be pulled from their atoms or molecules causing ion pairs (free negative electrons and positively charged atoms or molecules). These ionizing events (quantum transitions) result in energy transfer from the incident particles to the atoms and molecules. This energy transfer results in a slowing down of the incident particle. When the energy of the particle is very high the relative frequency of these noncatastrophic quantum transitions per unit path length is not very great, and the fraction of the total energy lost and consequent velocity reduction per event is very small. At lower particle energies, the lower velocity permits a particle to be in close proximity to an atom or molecule for a greater period of time. This permits the electrical forces exerted by the charge of the particle on the electrons of the atom or molecule to do more work, and this is exhibited as a greater amount of ionization per unit path length. However, even at these lower energies, the relative energy loss per ionizing event is exceedingly small, and the deceleration process is seen as a dense, virtually continuous ionized track with the particle suffering very little deflection from a straight-line path.

At very high energies, the particles may react with atomic nuclei resulting in the disintegration of the struck nucleus and the incident particle into many fragments. The energy of the incident particle will then be distributed among the fragments. These fragments, or secondaries, expend their energy by other means which also are dependent on

their energy and charge. This may include other less energetic disintegration events, but most of the energy is ultimately expended by ionization as just previously described.

Figure 72, a photograph of a balloon-borne experiment at high altitude, shows the tracks in emulsion made by a heavy primary particle upon striking the nucleus of a carbon, nitrogen, or oxygen atom. Note the ionization produced by the heavy primary particle is not as great as that produced by some of the less energetic secondary particles.

Electrons

The two modes of energy transfer just described apply to electrons as well as to positively charged particles, but in addition there is a third mode most often associated with electrons known as bremsstrahlung, the emission of electromagnetic radiation as particles abruptly decelerate on passing close to atomic nuclei. The photons emitted from this interaction may range in energy up to all of that of the parent electrons, the probability of higher energy x-rays increasing with higher energy electrons. Normally, electrons are scattered and slowed to a stop without penetrating deeply, though the bremsstrahlung produced may have considerable penetrating ability.

Neutrons

Although neutrons do not represent a consequential fraction of the total space radiation, two types of neutron interactions are important in radiobiology: elastic scattering and absorption. The more important of these in space is elastic scattering because this process occurs from the collision of "fast" neutrons (those of energy above 0.5 Mev) with atomic nuclei in tissue. Elastic scattering is the rebound effect between impinging neutrons and atoms. In tissue, such scattering is primarily due to hydrogen. Upon being struck by neutrons, the hydrogen atoms lose their electrons, and the resulting recoil protons cause ionization and excitation along their paths through tissue in the manner of positive ions discussed previously.

Slow neutrons tend to be captured or absorbed by the atomic nuclei more readily than fast neutrons. These absorptions usually result in an essentially simultaneous emission of other radiations which includes gamma rays. Several examples of reactions in which positive particles are emitted when slow neutrons are absorbed are N^{14}(n, p)C^{14}*, B^{10}(n,

* This nomenclature is read as "A neutron, n, enters the nucleus of a nitrogen atom of atomic weight 14, N^{14}, and a proton, p, is emitted leaving the nucleus as a carbon atom of the atomic weight 14, C^{14}."

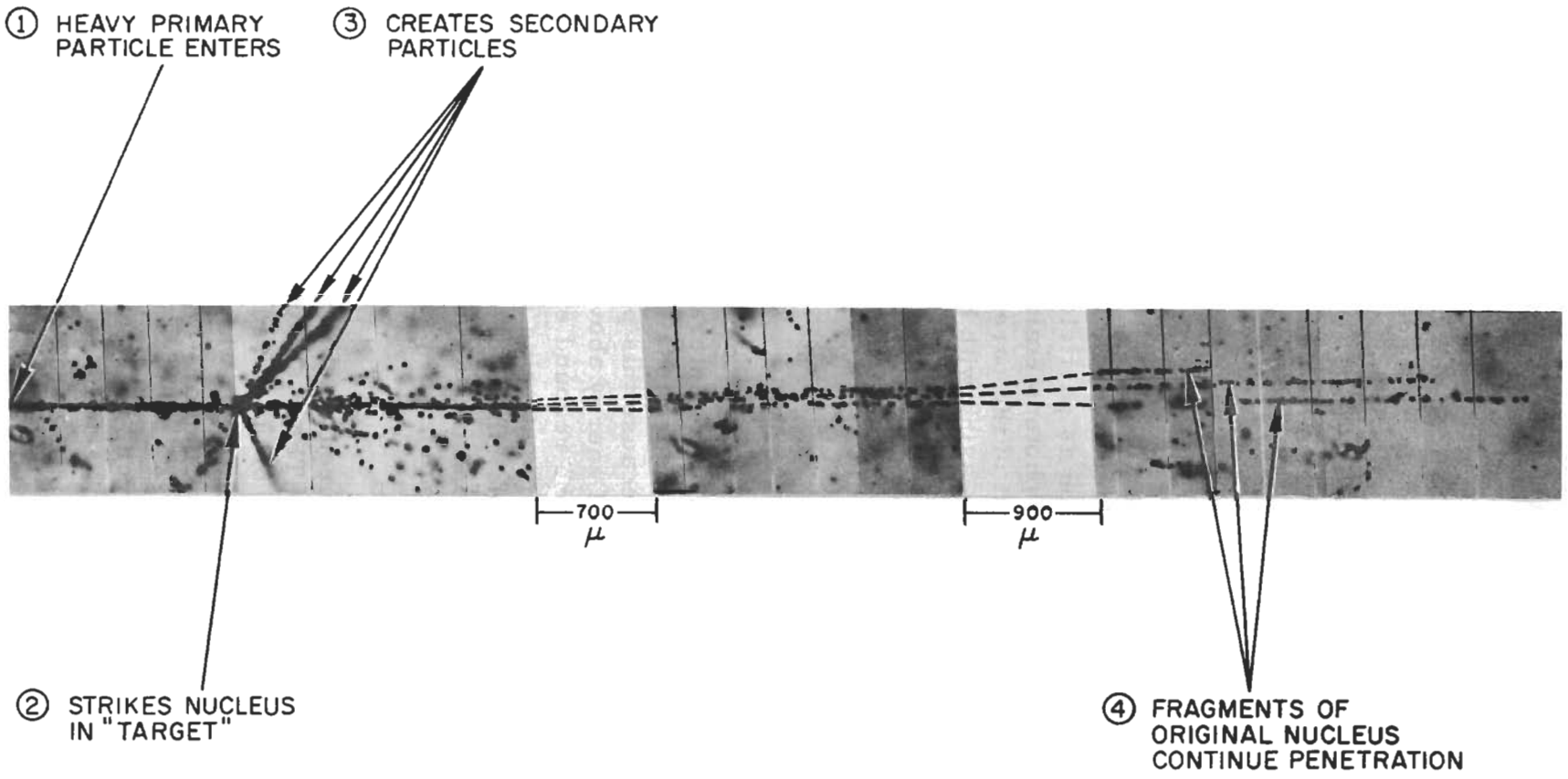

Figure 72. Interaction of high energy cosmic ray particle in emulsion. Tracks are made by ionizing primary and secondary particles. (Photograph courtesy of M. M. Shapiro and N. Seeman, Naval Research Laboratory.)

$\alpha)Li^{7}$, $Li^{6}(n, \alpha)H^{3}$, $V^{51}(n, p)Ti^{51}$, and $Ga^{69}(n, p)Zn^{69}$. More commonly, when a slow neutron is absorbed there is an emission of gamma radiation, and the original atom goes up in atomic weight by one. This new atom may or may not be a radioactive isotope.

X-Rays and Gamma Rays

The distinction between x- and gamma rays is somewhat arbitrary; generally, these very short wavelength electromagnetic radiations are classified according to source (x-rays arising from bremsstrahlung, and gamma rays from excited nuclei) or according to wavelength (the very shortest being termed gamma rays). Ionization from x-ray photons can occur through three processes: photoelectric absorption of photons by atoms with a resultant ejection of electrons; by Compton scattering in which only a portion of the photon energy is absorbed, resulting in ejected electrons and photons of lessened energy; and by pair production absorption in which the photon energy is converted into pairs of electrons and positrons.

Thin-Down Hits and Disintegration Stars

The one phenomenon of space radiation which is unique, compared to man-made and naturally occurring terrestrial radiation, is the occurrence of enormously energetic ions of high atomic number in the radiation of cosmic origin. Such particles tend to pass through the body with relatively little damage because the specific ionization, or rate of energy loss (REL), is low in comparison to particles of lower velocity. But if these cosmic rays or other high energy particles come to rest in tissue, the damage can be increased manyfold in the short space that the remaining energy is suddenly absorbed. There are two processes by which this can come about: the disintegration star and the thin-down hit. Each results in very high local specific ionization.

The term, specific ionization, is defined as the number of ion pairs produced by a charged particle per unit of path length. The quantity is directly proportional to the square of the charge of the particle and inversely as the square of its velocity.

Above a certain energy, about 1 Bev/nucleon, particles either pass through tissue with relatively low specific ionization or end in collision with tissue nuclei. The latter effect results in disintegration stars. Each subparticle produced then ionizes along its path. This multiplication of particles is not as destructive as it may seem for each of these fragments carries a smaller individual charge than the parent nucleus and the effect is spread over a greater volume of tissue.

Figure 73 is a good example of a star: the track of the parent high energy proton indicates low specific ionization until the collision occurred, whereupon a number of subparticles were produced which ionized more heavily in various directions. A jet of mesons continued on in the forward direction; this is shown by the sharp cone of lightly ionizing tracks to the right of the star.

At lower energy levels, less than about 1 Bev/nucleon, ions do not have high penetrating power for tissue and will release their residual energy by heavy ionization along their path. This is the terminal thin-down phenomenon which results in exceedingly high doses to individual cells. Such cells may become devitalized because of the great density and diameter of the ionization column. They may each receive in their full volume a dose of several thousand r.[2]

Figure 74 illustrates a terminal thin-down in emulsion. The heavily ionizing nature of this particle, estimated to have had a charge of 12, is apparent. The region of greatest ionization immediately preceding the thin-down is shown in the upper photograph. The lower photograph shows the thin down itself.

The probability of star production decreases with decreasing energy of the penetrating particles; hence, at lower energy levels there is an increasing probability that the particles will undergo thin-down rather than collision. Below about 0.1 Bev/nucleon the probability of star production is essentially zero so that nearly all incident ions that terminate in tissue do so in the abrupt, destructive thin-down manner. This being the case, it is clear that shielding which slows down the ultra-high energy cosmic ray particles may actually result in greater radiation damage to space craft occupants. It is often said in this respect that no shielding is better than any which could be practically provided. About the only means of protection from these cosmic ray particles is to limit the exposure time.

One of the purposes of this Guide is to help its readers understand and appreciate the true implications of the hazards from space radiations. Lest the foregoing on thin-downs be taken with alarm, let us discuss this effect on a larger scale. Each cell affected by a thin-down hit does not necessarily die, while many of those which do may be regenerated. In consequence, the only important damage from these hits occurs when the ionization may become "biologically amplified" to affect neighboring cells, or when a whole group of cells is disrupted outright, or when nonregenerating cells are struck. The intensity of particles which are likely to undergo thin down should be very low if shielding is provided from solar protons and Van Allen radiation; therefore, these remaining

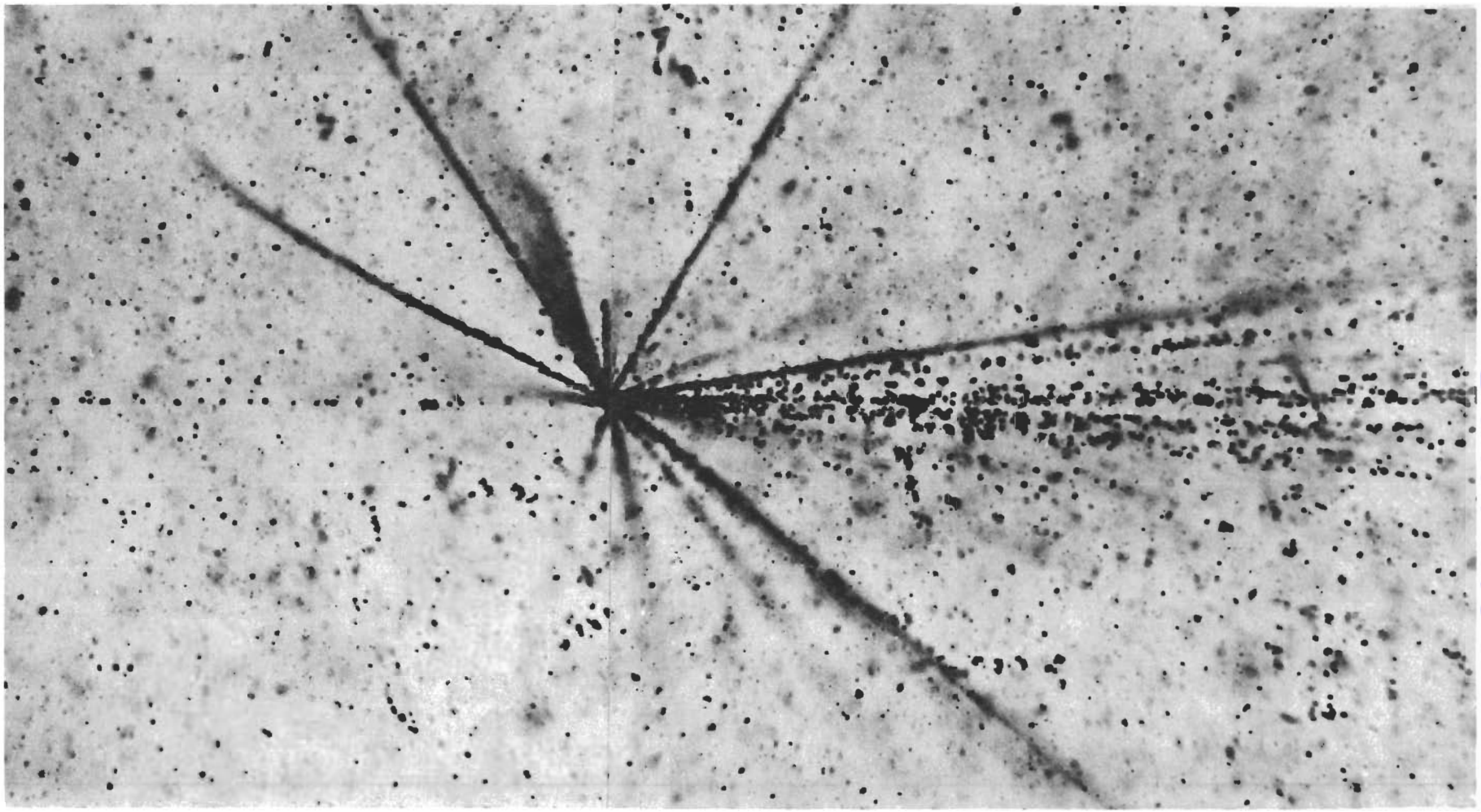

Figure 73. Star initiated by a high energy proton. Note the relative ionization densities of the incoming particle on the left, the subparticles of the star, and the "cone" of mesons continuing to the right. (Courtesy of Dr. H. Yagoda, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.)

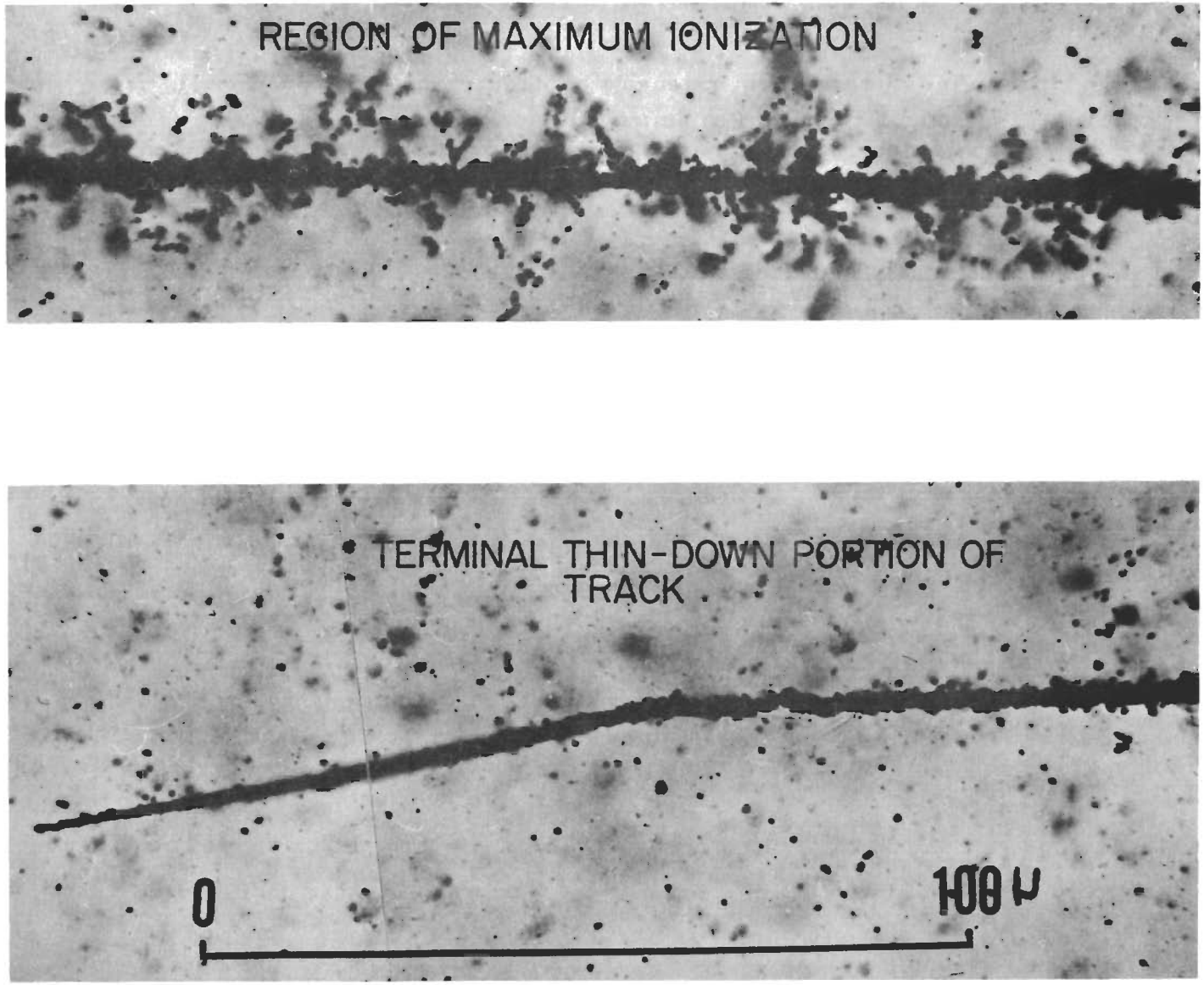

Figure 74. Heavy primary (charge of about 12) in the final stages of penetration. Upper photo: Track immediately preceding the thin-down. Lower photo: Track of the thin-down as all energy was spent. Both photos illustrate the dense ionization resulting from this type of phenomenon. (Courtesy of Dr. H. Yagoda, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.)

particles which are not shieldable should inflict very minor physiological effects on crew members in space.

A widely publicized experiment exposing mice to cosmic rays at the top of the atmosphere resulted in only one observable type of damage--a few random hairs changed color. Other damage which could occur would be the destruction of a cell or group of cells vital to some body function, such as might be in the nerves or brain. A hit on the retina, for example, might result in a small but permanent defect in eyesight.[3] Genetic damage is probable to some degree. The probabilities of occurrence of such events are not known, but from the few balloon and satellite experiments on animals, we may infer that there will be no drastic damage from this unshieldable component of galactic cosmic rays.

HUMAN RESPONSE

Having just touched on the way in which the various types of space radiations interact with tissues, let us next examine the effect of such ionization on the well-being of crew members exposed to this environment. Here, too, the literature on the subject is extensive and the following is a greatly condensed summary of the most salient effects.

Caution should be used when drawing conclusions as to the effects of a given dose. In addition to the before-mentioned uncertainties in predicting specific response, there are other factors which are of extreme importance. Among them are: the rate at which radiation is absorbed, previous exposure of an individual, the manner in which the exposure takes place (whole-body or part-body, omnidirectional or discreet source direction, etc.), and the penetrating ability (energy) of the kinds of radiations contributing the dose.

First, consider the effects of a single exposure of the whole body to x-rays. The subject has been succinctly presented in reference 4, and a summary is included here in Table XI and Figure 75. An outline of various doses and their corresponding probable effects is presented verbally in the table; this information is then shown graphically as incidence of sickness or death as a function of dose. Note in the graph that ranges are expressed rather than specific quantities. For example, an acute dose of 150 r will result in sickness of from about 10 percent to 30 percent of the exposed individuals; or from another standpoint, 20 percent of the crew of a space craft could be expected to become sick from single doses between 125 r and 180 r and to die from single doses between 315 r and 385 r.

TABLE XI

Expected Effects of Acute Whole-Body Radiation Doses

Acute Dose (roentgens)	Probable Effect
0 to 50	No obvious effect, except possibly minor blood changes.
80 to 120	Vomiting and nausea for about 1 day in 5 to 10 percent of exposed personnel. Fatigue, but no serious disability.
130 to 170	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 percent of personnel. No deaths anticipated.
180 to 220	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 50 percent of personnel. No deaths anticipated.
270 to 330	Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20 percent deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months.
400 to 500	Vomiting and nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50 percent deaths within 1 month; survivors convalescent for about 6 months.
550 to 750	Vomiting and nausea in all personnel within 4 hours from exposure, followed by other symptoms of radiation sickness. Up to 100 percent deaths; few survivors convalescent for about 6 months.
1000	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
5000	Incapacitation almost immediately. All personnel will be fatalities within 1 week.

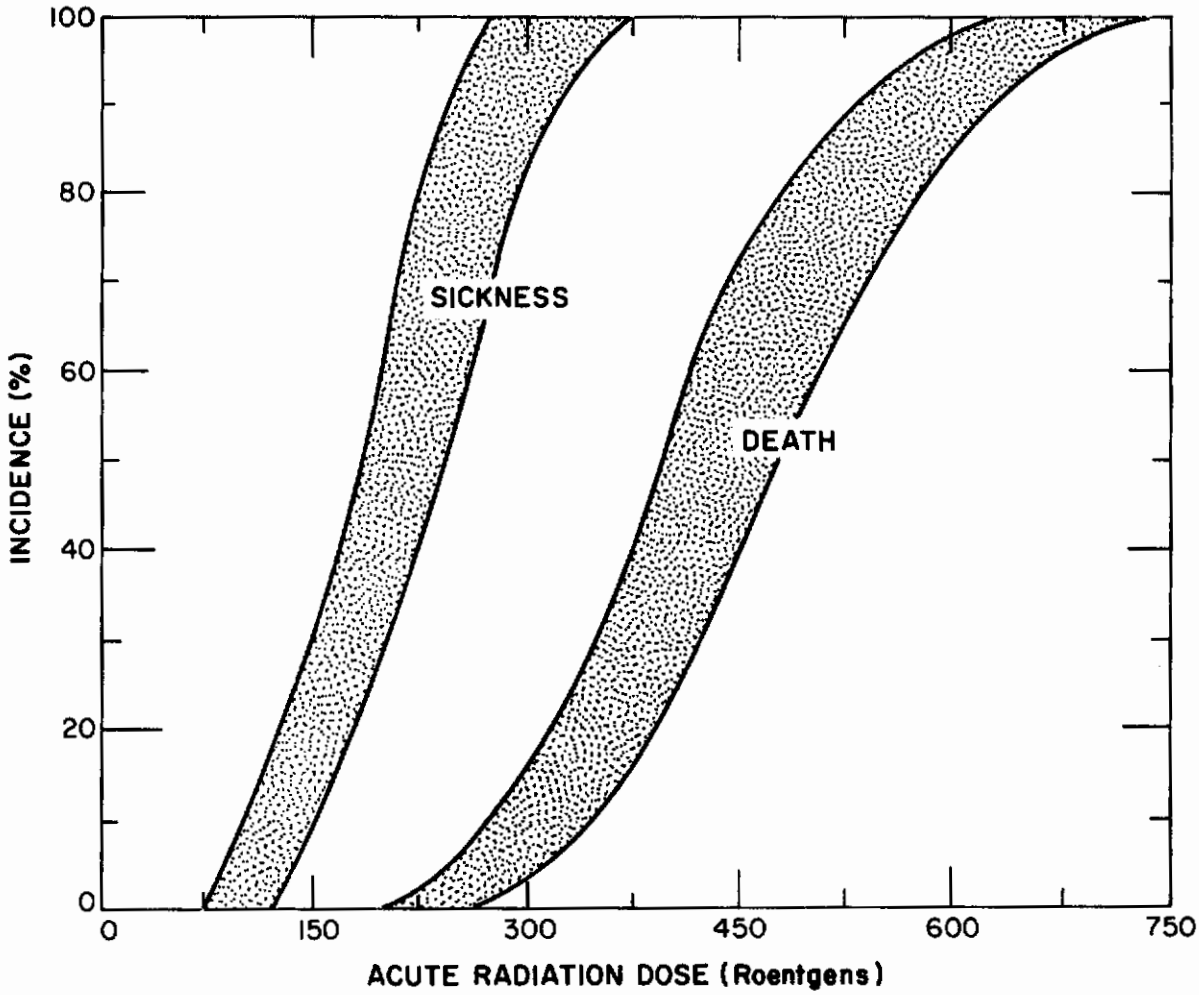

Figure 75. Incidence of sickness and death from acute radiation doses.

We cannot escape from the fact that in anticipating effects of such massive doses we are dealing with probabilities. Doses on the order of those just mentioned are not inconceivable if a space craft were to be caught in an outburst of solar protons. Whether or not a crew could continue to function properly under such a set of assumed conditions is open to conjecture. We are faced with double uncertainty: not only is it improbable that a particular dose can be predicted accurately, it is impossible to say just exactly what the effect will be.

A familiar expression in radiobiology is LD_{50}, or that dose which would be expected to be lethal to 50 percent of the exposed individuals. From Figure 75 it can be seen that for man the LD_{50} is between 400 r and 475 r.

We have just seen the result of acute doses in general terms of sickness. Let us consider briefly the sensitivity of certain organs, beginning with the most sensitive. The eye lens is highly susceptible to ionizing radiations, particularly so to neutrons. Cataracts can be induced by exposure to only a very small dose. Blood and blood-forming organs are very sensitive. Observable changes in this organ system can be detected very soon after irradiation. Quite small doses to the reproductive organs result in sterility, though the other body functions remain undamaged. The digestive tract is second only to the blood-system in determining survival after whole-body irradiation. Relatively insensitive is the circulatory system--post-irradiation changes usually show quick recovery. The central nervous system is exceptionally radioresistant, except for the brain, and even it is only sensitive to doses grater than LD_{50}. Figure 76 shows doses at which various effects occur in the body. Heavily shaded portions refer to observed experiments with mammals, while the lightly shaded extensions indicate that the effects may be detectable at lower doses. The graphical representation was adapted from reference 5.

In addition to somatic and genetic damage, there is another type of effect from ionizing radiation which should be considered as a hazard to space travel. This is life-span shortening, or a process of age acceleration. For obvious reasions it has been difficult to assess accurately the relation of radiation to such long-term effects in man, but there is no doubt of its existence in animals. Moreover, there are conflicting evidences concerning the effect on aging from both total dose and dose rate. There appears to be a linear relationship between the reduction of life span and dose for single exposure to x-rays and neutrons of about 4.7 percent shortening of life span per 100 r of whole-body irradiation according to reference 6. This would amount to around 3.5 years per 100 r, a considerable variation from the estimate given in reference 7 of perhaps 7 years per 1000 r.

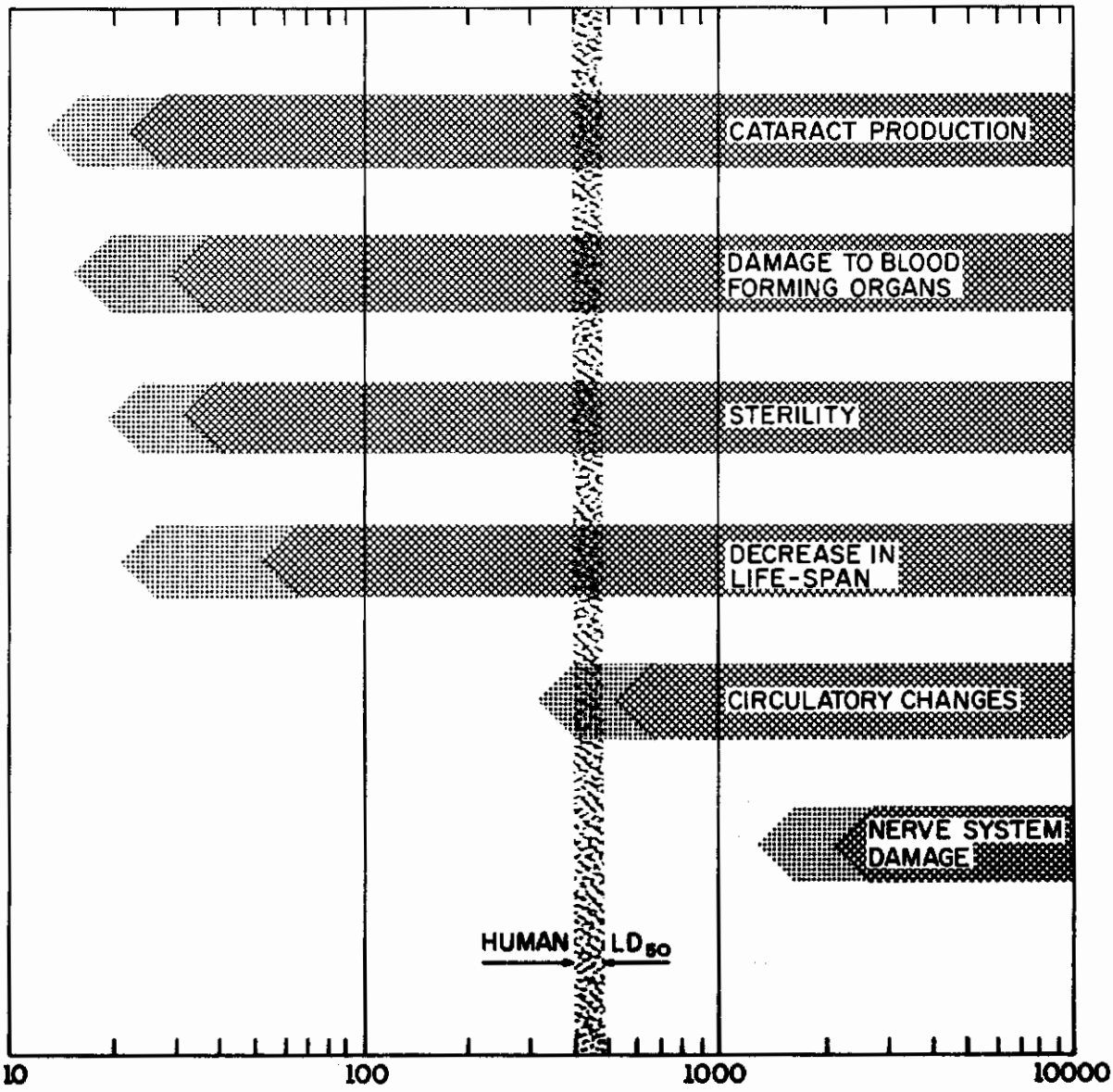

Figure 76. Radiation doses at which various physiological effects occur. Heavy shading represents experimental evidence from mammals; light shading refers to doses which might produce detectable changes in humans.

BIOLOGICAL PROTECTIVE MEASURES

Shielding of crew compartments is presently the only satisfactory method of protecting man from radiation in space. However, several possibilities exist which may eventually become useful as prophylactic measures. A short review of these possibilities is included in order to acquaint the reader with a field which may some day become of great importance in aerospace medical technology.

Chemicals

Chemical protection is perhaps the most promising type of prophylaxis. Certain substances have been found to decrease sensitivity of mammals to radiation. So far, however, chemicals which have shown a definite tendency to provide tolerance to radiation are toxic themselves to a degree which prohibits their use for space crew applications. Work in chemical protection is continuing, and it is likely that there may come about a drug which will significantly increase man's radioresistance without harmful side effects. Experiments with small mammals (mice) appear to be noteworthy indicators, as some chemicals have demonstrated the ability to produce a remarkable increase in survival probability of animals which received an otherwise lethal dose of radiation.[8]

It should be emphasized that the presence of chemicals reduces or prevents radiation damage before exposure, but is ineffective after the damage has occurred.[9] Whatever protection is afforded by a drug probably comes about by affecting molecules in such a way as to make them less likely to react with free radicals, or perhaps the chemical competes with biological molecules for the free radicals produced by radiation. A third possibility is that the drug may in some manner reduce the quantity of free radicals formed by the ionizing radiation. A better understanding of these modes of protection would offer an increased degree of selectivity in choosing compounds with which to experiment. As may be supposed, many substances have been and are being tried--from simple gases and inorganic compounds to complex organic compounds and biological materials, hormones, and dietary products.

Bone Marrow

A very promising agent for treatment after severe radiation injury appears to be an unirradiated supply of blood-forming cells. One feasible way to accomplish this is injection of a suspension of bone marrow. It has been found that functional breakdown of the blood-forming cells in the body after large radiation doses is a major cause of infection, hemorrhage, and anemia, and that injected bone marrow settles in the damaged marrow where it grows and replaces destroyed tissues. This new marrow

then quickly begins to replenish blood components, thereby preventing the above-named maladies.

Whether or not bone marrow injection will offer a useful first-aid emergency procedure in space remains to be seen. Problems in effectiveness, in administering the injection, and in obtaining and preserving the marrow are still unsolved; but there is reason to believe that these are not insuperable problems. Bone-marrow injection has increased the percentage of survival from ordinarily lethal doses in rats, hamsters, rabbits, dogs, and monkeys. In a reactor accident in Yugoslavia, five victims were treated with donated bone marrow; their survival was thought to have occurred largely as a result of this treatment, though the evidence was not conclusive. Preservation of bone marrow and other blood-forming tissues has been investigated and has been found to be feasible for both short and long terms. A suggested source of bone marrow, which might have application for a space craft medical kit, is from the individual crew members; this marrow could perhaps be stored in a shielded container for use in an emergency. Similar in effect to this idea, and probably more practical, is partial body shielding, whereby bone marrow in a heavily shielded region, such as one leg, would remain undamaged and become equivalent to a self-donated marrow transplant.

Adaptation

It has been suggested that adaptation to radiation might offer protection. Though a variety of human and animal tissues have been demonstrated to have this ability, there has been no evidence that adaptation to whole-body radiation occurs.[10]

SECTION V

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SECTION VI

INSTRUMENTATION

Man must have protection against the hazards of tissue-damaging radiation from the fluxes of high-energy particles in space. Evaluation of the personnel hazards arising from this ionizing radiation in space is a prerequisite to long-period manned space flight. The degree of protection necessary against this radiation is dependent upon the resident time in space and the type, quantity, and energy of the radiation encountered during a mission.

THE RADIATIONS TO CONSIDER

Let us review some of the presently available information on the various components of extraterrestrial radiation as an introduction to instrumentation and dosimetry problems.

Primary Radiation

Essentially all of the electromagnetic radiation above the earth's atmosphere is of such an energy and intensity as to be completely shielded by almost any vehicle wall thickness. As a result, this type of extraterrestrial radiation should comprise no human hazard.

Available information indicates that no neutrons are present in the primary radiation and that neutrons detected outside the earth's atmosphere are born in the atmosphere and diffuse out. The neutron flux in and outside the earth's atmosphere is so small that no hazard is expected, and consequently no shielding for this type of radiation is required.

The electron flux in space (the outer Van Allen belt) is similar to the electromagnetic spectrum in that it can be easily shielded without special materials or thicknesses. The vehicle wall thickness is probably sufficient to shield against the naturally occurring electrons. However, a problem will be created by the bremsstrahlung produced as these electrons are being stopped. The bremsstrahlung production is a function of the atomic number of the stopping medium, so the problem can be minimized by employing low Z materials in the external vehicle wall.

Very high-energy protons, because of their ability to penetrate matter, present a major shielding problem and are the main radiation hazard to occupants of space vehicles. The chief sources of this radiation are the inner Van Allen belt and solar flares. As noted in previous

sections, the intensity and energy of the proton radiation to be encountered in any space mission remain an uncertainty and cannot be forecast with accuracy before a mission is started. Before any exact assessment can be made of the radiobiological hazard to be encountered in any space mission, and before the required shielding necessary to prevent a hazard can be determined, the average fluxes and energy spectra of this proton radiation must be established with more precision.[1]

Secondary Produced Radiation

In any complete analysis of the dose rates associated with ambient space radiation, one must consider secondary radiations produced by the interactions of the incident radiation with the stopping medium (the walls of the space vehicle and the human body). The predominant constituents of this secondary radiation are photons (bremsstrahlung) emitted as a result of electron interactions with the bound electrons of the atoms of the stopping materials; and secondary particles, predominantly neutrons, emitted as a result of proton interaction with the atomic nuclei of atoms of the surrounding materials. Before one can determine whether a radiobiological hazard exists as a result of this radiation or determine the shielding required for protection, one must know the intensities and spectra of the incident particles causing this secondary radiation, the materials comprising the shielding and the space vehicle walls, and the reaction cross sections for producing this secondary radiation.

INSTRUMENTATION FOR MEASURING RADIATION FIELDS

The extremely wide variation in the intensity and energy of the various species of space radiation, together with the specific requirement of the measurements necessary for a significant aeromedical evaluation, prevent the construction and use of a single instrument to perfrom intensity and energy determinations and analyses for all the species of radiation. However, a system of instruments can be devised which will permit such determinations and analyses of all expected radiation to enable a satisfactory determination of biological dose rates and doses from an aeromedical standpoint.

Table XII shows the order-of-magnitude estimates, from available information, for the particulate populations in space that must be evaluated. While the numbers are crude estimates, they do point out the need for exact measurements of this space radiation for biological hazards determination.[2]

For investigation of the various constituents of the space radiations, Figure 77 shows a summary of the portions of the particle

TABLE XII

Order-of-Magnitude Estimates
For Particulate Populations

	Concentration, Particles cm^{-3}	Particle Flux, Particles cm^{-2} sec^{-1}	Energy Flux, Bev cm^{-2} sec^{-1}
Solar Proton Wind (kev)	10^{2} to 10^{4}	10^{9} to 10^{12}	10^{3} to 10^{7}
Earth's Radiation Belts (Mev)	10^{-5}	10^{3} to 10^{8}	10^{2} to 10^{6}
Galactic Cosmic Rays (Bev)	10^{-10}	1 to 4	1 to 4
Solar Cosmic Rays	----	10^{2} to 10^{4}	----

spectrum that can be measured by several detection systems which could be made compatible with space vehicles. Figure 78 shows some of the instruments that can be used to detect the secondary radiations. The dynamic range of the instruments must be chosen to measure the radiations associated with a quiescent sun as well as those associated with solar disturbances. Detection systems now being studied and tested for integration into future satellite and missile space programs include various combinations of instruments, such as those shown in Figures 77 and 78--the combinations depending on the information being sought.[3,4,5]

DOSIMETRY CONSIDERATIONS

Exposure doses from particulate radiation have little significance in a biological sense. For biological specimens, the important consideration is the amount of energy absorbed in a given volume or mass of tissue. An adequate instrumentation system for personnel-hazards analysis of space radiation must provide information on the absorbed dose as a

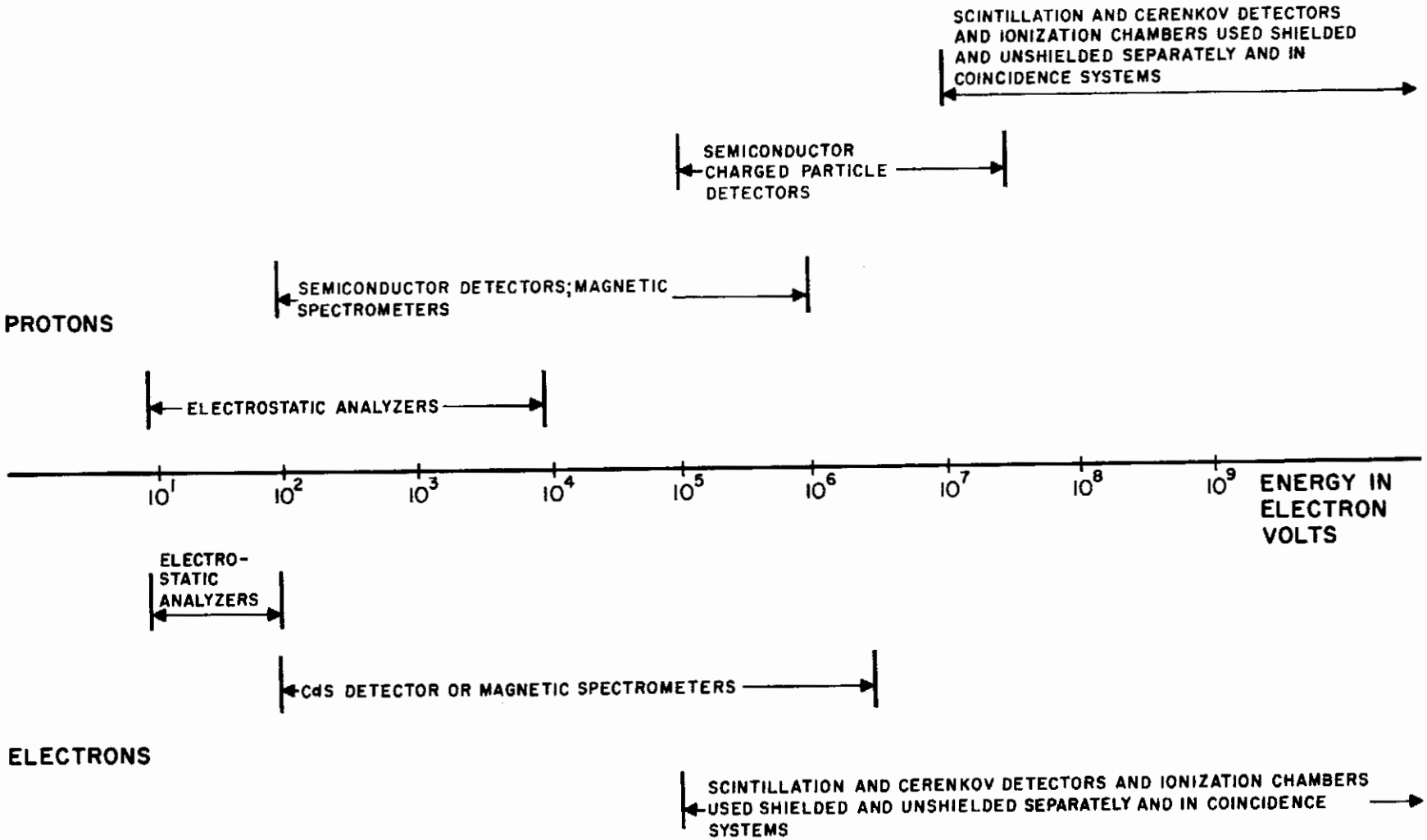

Figure 77. The energy ranges of radiation detection systems for the important primary radiation within a space vehicle crew compartment.

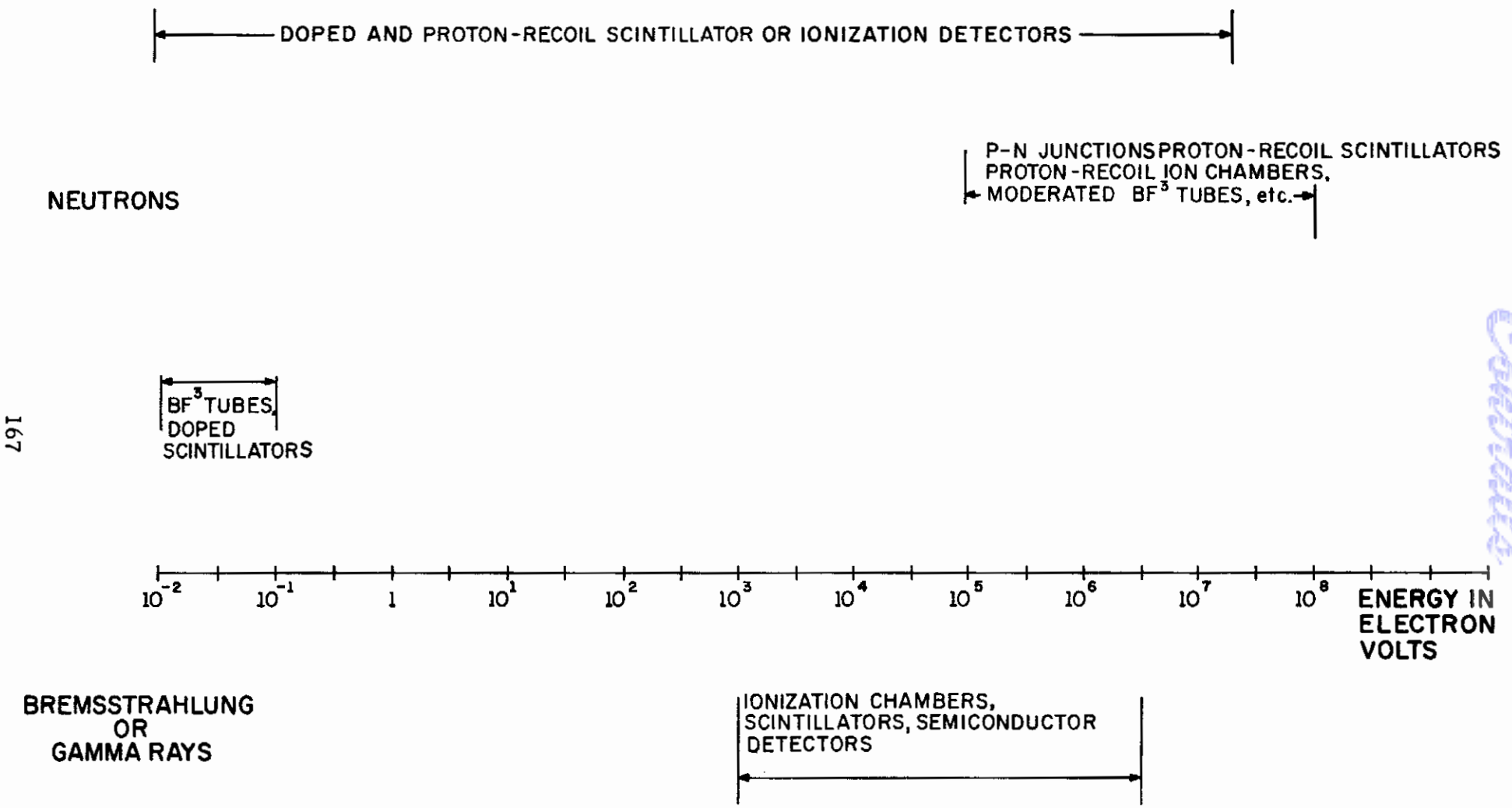

Figure 78. The energy ranges of radiation detection systems for the important secondary produced radiations.

function of depth within a man's body since tissues vary in their radiosensitivity. Therefore, it is important that the absorbed energy dose for a given volume of tissue from each type of ionizing radiation be expressed by a standard unit such as the rad--defined as the amount of radiation which will result in the absorption of 100 ergs per gram of material. Once this dose information is obtained for each type of radiation, the RBE (Relative Biological Effectiveness) factor for each type of radiation can be applied to determine the hazard presented by the radiations. This RBE factor for each type of ionizing radiation depends on the linear energy transfer (LET) of the radiation and on the particular tissue and biological response under consideration. The true biological hazard due to each type of radiation is expressed in dose units of Roentgen Equivalent Man or rem, and can be expressed as rem = rad × RBE. To determine the absorbed energy depth dose profile for particulate radiation, one must know:

1. The energy spectrum and intensity of the radiation incident on the tissue.

2. The range of the particles in the tissue under consideration.

3. The linear energy transfer (LET) of the particle as it passes through the tissue.

Figure 79 gives an estimate of the absorbed dose per unit flux in a thin sample of tissue material for various primary particle radiations. The corresponding curves for particles of higher Z would be Z^2 times those shown for protons.[6] The absorbed dose per unit flux for different particles of a given energy, as shown in Figure 79, is directly related to the linear energy transfer (LET) of each particle type. This clearly indicates that the LET of a particle, as it is being absorbed, increases as its energy decreases. This is demonstrated in Figure 80, which shows this dependence over the last 50 microns of the proton range in tissue.[7] If the incident protons were monoenergetic, and of low enough energy, it is evident that at some particular depth in tissue there would be a sharp peak in the absorbed energy dose rate. Since the protons in both the Van Allen belt and solar flares have a broad spectral distribution, this does not occur. The differential energy spectrum of the protons in these fields is such that the proton flux or intensity decreases with increased energy. This results in the dose rate being maximum at the surface. Figures 81a and 81b show the relative depth dose in an hypothetical 52 cm diameter spherical tissue phantom protected by different shield thicknesses for protons from the radiation belt and for protons of a solar flare approximately 1-1/2 days after termination of the flare.[8]

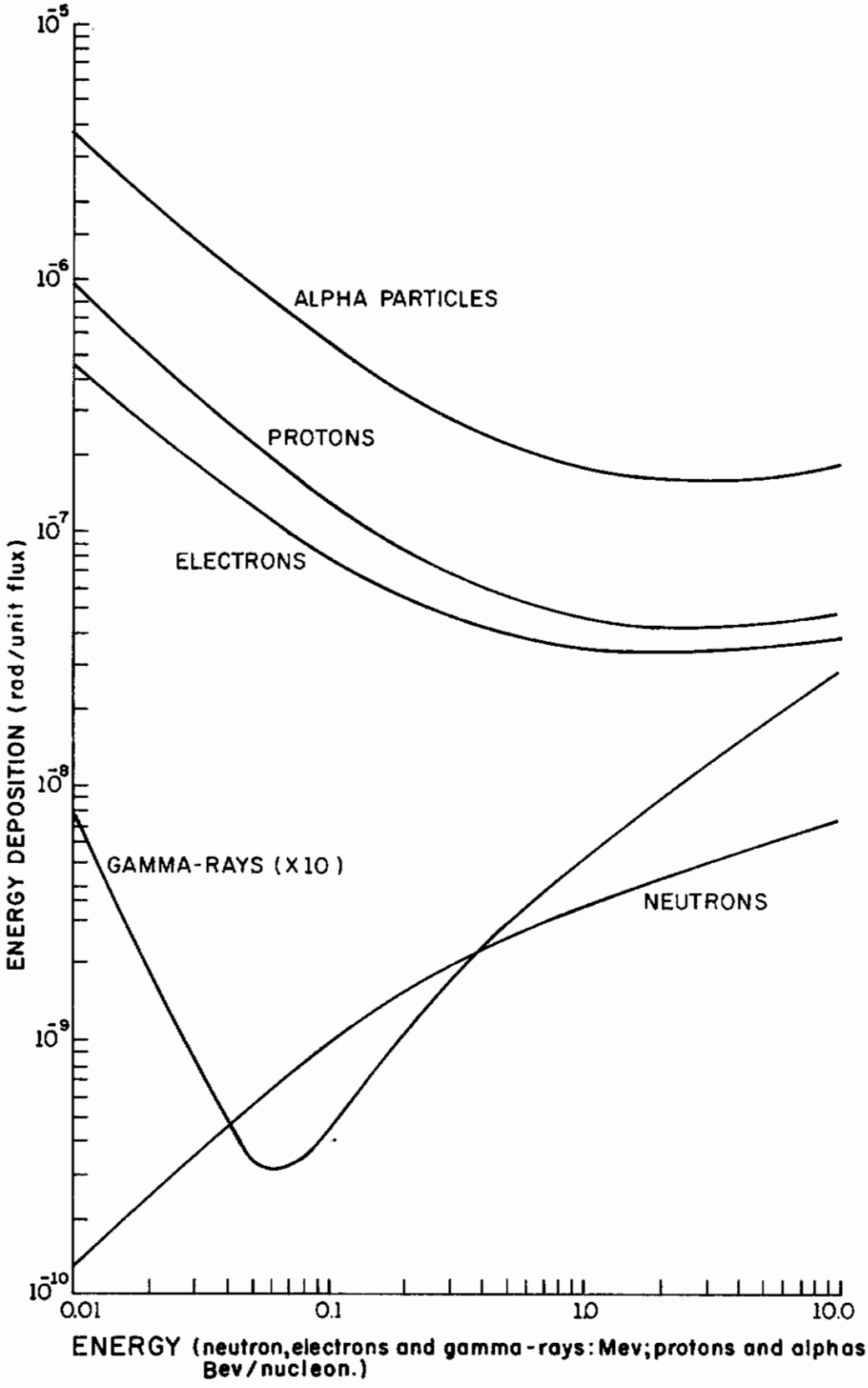

Figure 79. Energy deposition for unit particle flux in tissue material.

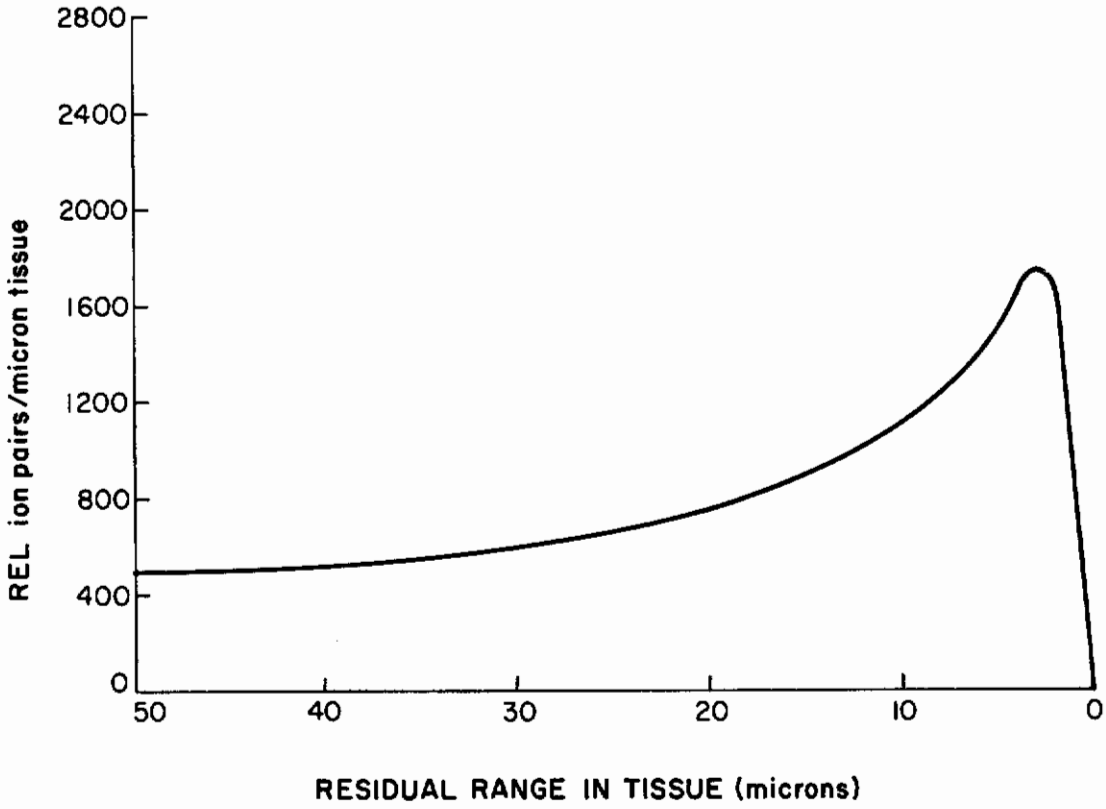

Figure 80. Relative energy loss for protons absorbed in tissue.

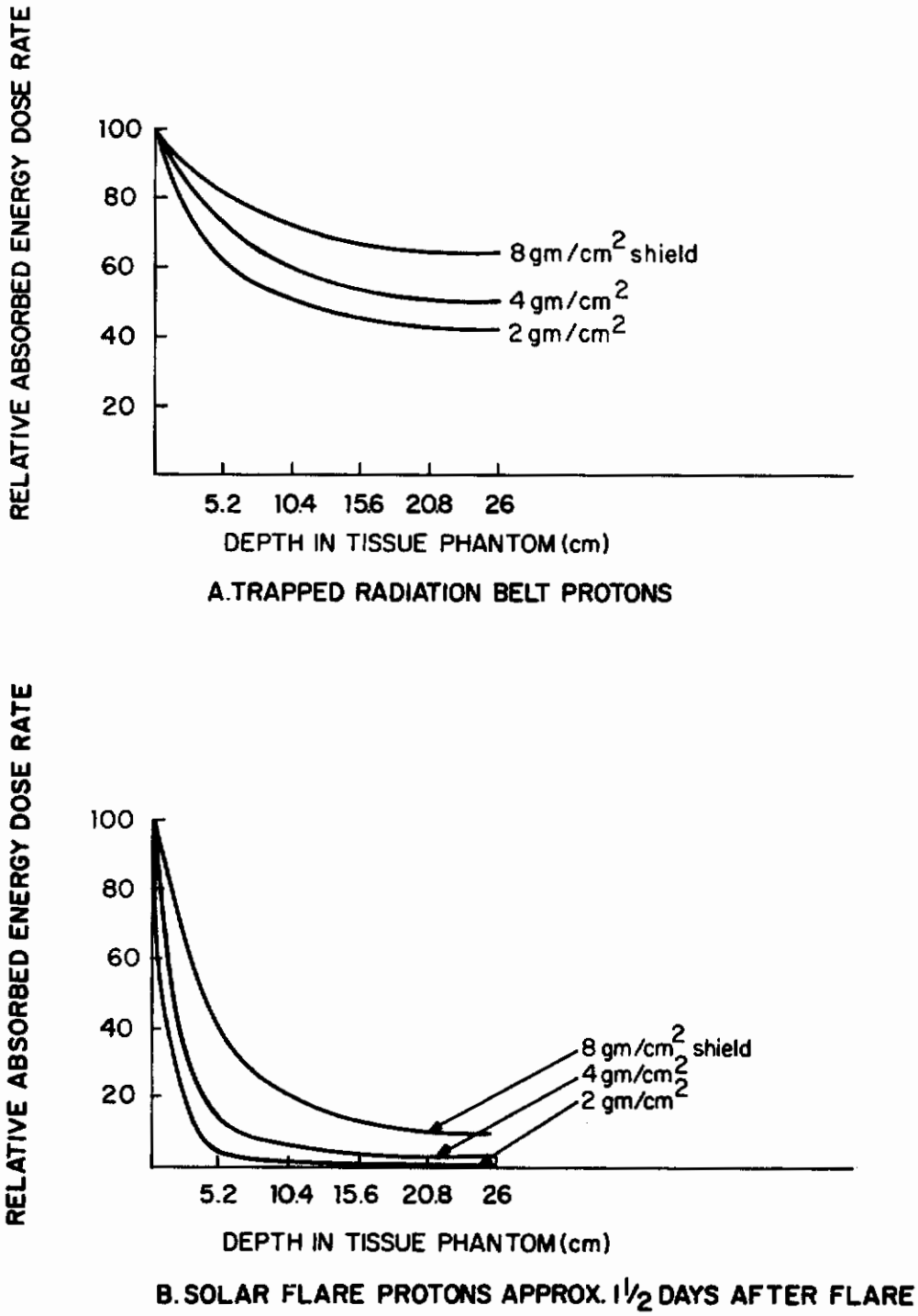

Figure 81. Relative depth dose in tissue for protons in the trapped radiation belt and a solar flare.

Vehicle shields will result in the radiation spectra inside the shield being different than those outside the shield. Once the radiation fields expected to be encountered inside a vehicle on a particular space mission are determined, then an instrumentation system might be designed which would have a response to each of the different types of radiation such that the output would be proportional to the energy absorbed in body organs of interest. It would also be desirable that the output of the detectors for the different types of radiation be weighted to account for RBE of the radiation it measures.

INSTRUMENTATION SYSTEMS FOR MANNED VEHICLES

Two general types of radiation detection instrumentation are needed in a vehicle for any extended space mission. One system would be required to monitor continuously the radiation intensity or dose rates, and the other system would be required to measure the doses accumulated during the course of the mission. The purpose of the first system is to provide the vehicle personnel with continuous information that will alert them as to what countermeasures must be taken to prevent overexposure. These countermeasures might include "taking cover" in special locations in the vehicle which are designed to provide additional shielding, taking radiation injury prophylactics (if such can be developed), or modifying the orientation of the vehicle with respect to its trajectory to provide additional "shadow shielding" if the radiation is directional. The purpose of the second system is to measure accumulated doses of each individual crew member so that overexposures can be prevented or limited. It would be preferable that each crew member be equipped with a system worn on and/or in his body which measures the actual dose he has received. However, by using electronic systems which integrate the output of the dose rate instrumentation, accumulated doses at any time for various locations within the vehicle might be determined. This might require the individual crew member to maintain a record of the doses he has received while in various locations in the vehicle, or perhaps the vehicle might have a computing system whereby each crew member could "clock-in" time spent in the different locations inside or outside the vehicle. The computing system could then compute and accumulate the doses received by each crew member. A requirement applying to any instrumentation system is that the accumulated doses for the various types of radiation be capable of easy "readout".

The state-of-the-art in dosimetric devices for heavy-charged particle radiation is not as advanced as for electromagnetic and electron radiation in the region from 50 kev to 2 Mev. It is anticipated that until

the state-of-the-art of pulsed type charged particle dosimeters is improved, most of the dosimeters that will be used for space radiation will be basically ionization chambers which rely on the Bragg-Gray principle. When certain requisite conditions are fulfilled, this principle relates that the energy deposited in the dosimetric device is proportional to the energy deposited in the surrounding medium. This method entails appropriate corrections for the relative stopping power of the surrounding material and the dosimetric material. Such dosimeters, as with nearly all dosimeters that can be envisioned, are subject to the frailty of having dimensions that are large with respect to critical cells or groups of cells. Thus, results are somewhat macroscopic, and single "hits" of critically important cells or groups of cells by particles with a high LET may not be detected. The most commonly used dosimetric devices that are employed in Bragg-Gray principle systems are miniature gaseous ionization chambers. However, cadmium sulfide and other semiconductor detectors, phosphate glass needle dosimeters, and Ca F(Mn) thermoluminescent needle dosimeters might be used if appropriate corrections can be made to compensate for the differences in stopping power between the dosimeter material and the tissue of interest.

If the vehicle configuration were such that the radiation intensity would be essentially uniform throughout the crew compartment, a possible system for measuring the abosrbed energy dose rates and doses would be a series of detectors imbedded in a sphere of tissue-equivalent materials. Detectors at various depths in the sphere would indicate the dose rates and doses received by organs of the body at different depths.

There have been attempts to utilize the radiosensitivity of some small animals for nuclear radiation dosimeters. Attempts have also been made to use the early observable effects of radiation on man, such as the reduction of binucleatul lymphocytes, acid neurophils, or chemical changes in nuclear NDA content, for dosimetry purposes.[9] All these biological dosimeter systems need further development to establish dose-response relationships before they can be used with the reliability and simplicity of physical systems. The wide range in response between individuals within a particular space group complicates the use of any biological dosimeter system.

If the space craft should be powered by a nuclear propulsion system, it would be necessary to monitor the associated radiation hazards. The state-of-the-art for monitoring gamma ray and neutron radiation hazards is quite advanced, and it is not considered worthwhile for the purposes of this work to elaborate on such dose rate and dosimeter systems. Perhaps the best source of information on such instrumentation is the periodic reviews prepared by the Battelle Memorial Institute.

There is evidence from some satellite experiments that radioactive contaminates, such as H^3, A^{41}, and C^{14}, are induced in the materials of the satellite by interactions with high energy protons. An evaluation of this problem for an extended space mission probably would indicate that the hazard presented by the induced radioactivity would be negligible in comparison to the hazards presented by the radiation that induces the radioactivity.

SECTION VI

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SECTION VII

SHIELDING REQUIREMENTS FOR MANNED SPACE FLIGHT

The discovery of previously unknown intense radiation fields in space has intensified interest in the penetrating ability of these radiations in manned space vehicles. Preliminary investigations of these fields indicate that the biological effects will present a prime deterrent to manned space flight. Owing to the serious implications of this hazard, the problem of shielding must be studied thoroughly before designs for extended manned space flight can be completed. In this section is discussed the passage of space radiation through matter and the subsequent protection against this radiation.

PASSAGE OF RADIATION SPECIES THROUGH MATTER

The penetrating particulate radiations of interest here are those associated with the space radiation environments; namely, the galactic cosmic radiation, the solar flare radiations, and the geomagnetically trapped particulate radiations (the Van Allen belts). Each of these types of radiation fields presents a potential hazard to manned space flight.

In a closer examination of the interactions of the relatively high energy penetrating space radiations with matter, it is convenient to divide the space radiation energy spectrum into three categories: (1) energies below 10 Mev--the predominant space radiation contributor in this energy range being the outer Van Allen belt electrons: (2) the energy range from 10 Mev to 1 Bev--the predominant contributors in this range being the inner Van Allen belt protons, solar proton outbursts, and, to a lesser extent, the low energy protons of the galactic cosmic radiation; (3) energies above 1 Bev--the contributors being the galactic cosmic ray protons and heavier nuclei and the relativistic protons associated with the infrequent, unusually large solar proton outbursts.

In addition to these more predominant penetrating space radiations, there are also present cosmic ray produced albedo neutrons; low energy protons, electrons, and bremsstrahlung associated with the aurora; and ultraviolet and x-ray emissions from the sun. All these latter types of space radiations are of little consequence from the standpoint of biological shielding since they are either of such a very low intensity as

to present a negligible hazard, or are of such a low energy (<100 kev) as to be easily stopped by nearly any thin material of a vehicle wall.

In considering category (3), the galactic primary cosmic radiation presents a more or less constant background radiation environmental factor to which any space vehicle would be subjected, with the relativistic solar flare protons causing transient increases in this constant background. It has been seen from the discussion in the preceding sections on the galactic cosmic radiation and relativistic solar flares that this radiation is composed of extremely high energy nuclei, principally protons. When this primary radiation is incident upon dense substances, a large number of secondary particles are produced. Provision of absolute shielding against primary particles is virtually impossible. It would require about 12 to 15 cm of steel to stop even the less penetrating heavier nuclei, and for 5 Bev protons it would require in excess of 30 cm of steel, not including shielding against the secondary produced particles.[1] Fortunately, however, the intensity of these primary cosmic particles is quite low; as a result the total intensity of the primary and secondary radiation inside a space vehicle under normal situations should not exceed tolerable dose rates. However, it is noteworthy that the heavy nuclei, which represent only about one percent of the total primary cosmic ray flux, contribute over 50 percent of the total primary cosmic ray ionization.[1] The chief biological damage resulting from heavy nuclei bombardment is derived from their high rate of energy loss (REL). It has been illustrated that a single thin-down hit of a densely ionizing charged particle can deliver serious localized damage to living tissue.[1] It is seen, then, that although the fluxes of these heavy nuclei are quite low, the amount of localized biological damage delivered to some specific body organ, such as the eye or other small critical organ, as a result of a single thin-down hit of a densely ionizing heavy nuclei may be quite serious. Since the question of the effects of heavy nuclei has not been completely resolved, it may be necessary to provide protection against this radiation, especially for space missions of extended duration.

The protons in the energy range of 10 Mev to 1 Bev (category 2) lose energy chiefly by inelastic collisions with atomic electrons via excitation and ionization processes in the stopping material. This causes a practically continuous reduction of energy as the protons penetrate through the medium. For protons of relatively high energy, some contribution to energy loss is due to interaction with the nuclei of the stopping medium with the subsequent emission of electromagnetic radiation or bremsstrahlung. However, for the proton of the energy range of interest here, this contribution plays a relatively minor role. Protons also can interact directly with atomic nuclei causing either direct ejection of one or more secondary particles from the original target nucleus, or they

may create an excited nucleus which stabilizes by the delayed emission of particles and/or gamma rays. The emitted particles from reactions of this type can include alphas, deuterons, tritons, single or multiple neutrons, betas, positrons, etc. Except for the neutrons, these secondary particles will be readily attenuated by shielding materials. Therefore, the most important nuclear reactions from a radiation hazard standpoint are the neutron-yielding reactions.

The intensity of the relatively high energy protons of category (2) is quite high, and as a result the dose rates and doses associated with this radiation are of considerable concern. Some form of radiation protection against this space radiation must be afforded for manned space flight.

The electrons in the energy range of up to 10 Mev (category 1) lose their energy in matter in essentially two ways: First, and the most predominant mechanism, is loss of energy through excitation and ionization with the bound electrons of the atoms of the material, as discussed in the case of protons. Secondly, the incident electrons can be deflected and decelerated by the electric field of the atomic nucleus and in the process emit electromagnetic radiation (x-ray photons). This secondary emitted electromagnetic radiation is termed bremsstrahlung. The bremsstrahlung photons produced have a broad spectral distribution and those of higher energy may have great penetrating power. This is the principal radiation problem for the outer Van Allen belt. Figure 82 shows the ionization losses for protons and electrons in aluminum and lead, and Figure 83 shows the radiative losses for electrons in aluminum and lead and the neutron production for protons in aluminum and lead.[2,3,4]

PROTECTION AGAINST RADIATION IN SPACE

Shielding Effectiveness

Before an exact determination of shielding effectiveness for a given space vehicle configuration and wall material for a given mission can be ascertained, one must know, with a reasonable degree of certainty, the types, intensity, spatial distribution, and energy spectra of the various particulate space radiation fields that will be encountered. Variations in these fields with regard to the time of solar and geomagnetic occurrences are vitally important. Information is also needed regarding attenuation and degradation of the various incident primary radiations through a variety of structural and shielding materials as a function of material thickness, and this information must be developed through calculations utilizing

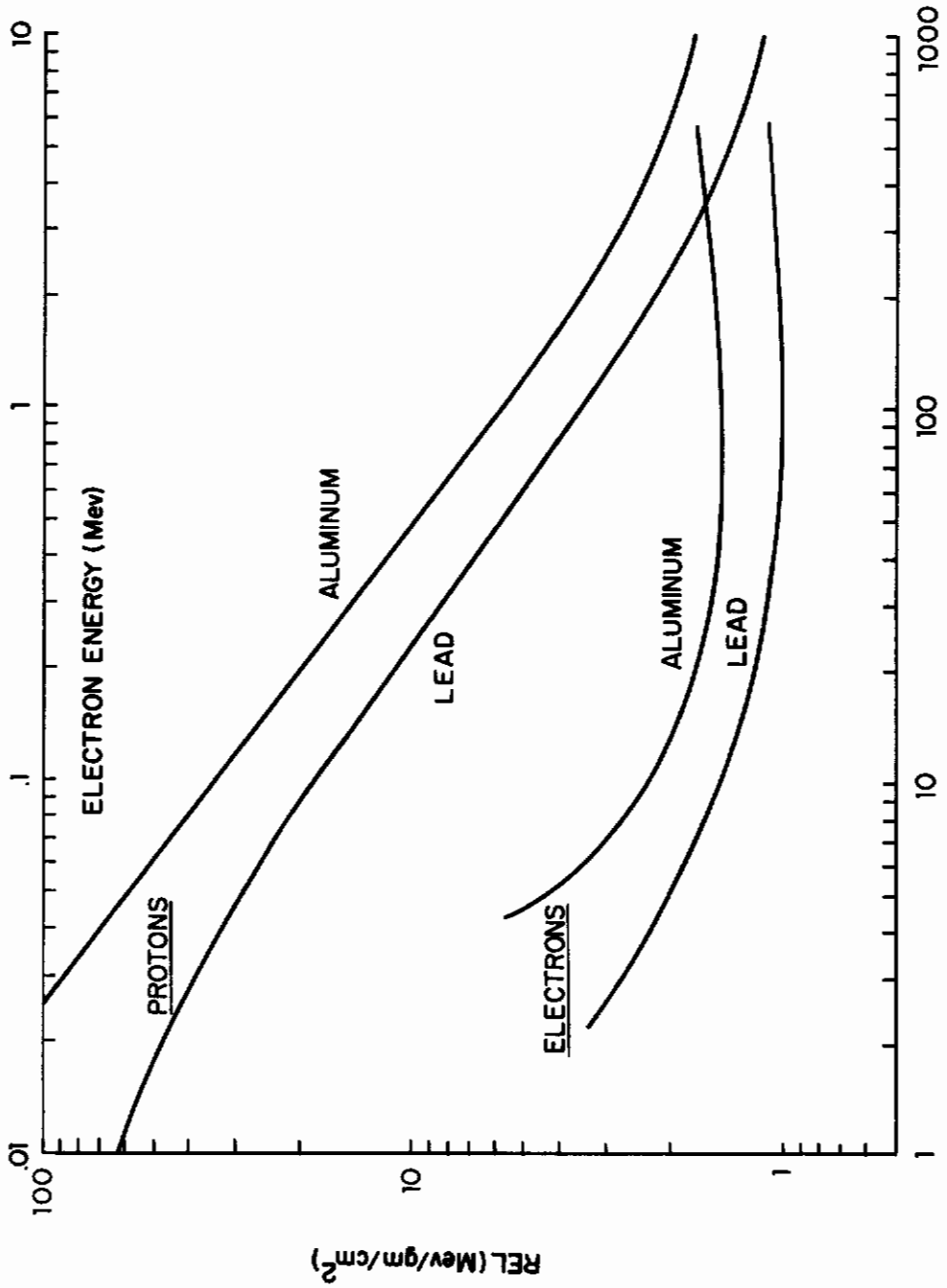

Figure 82. Average rate of energy loss, dE/dx, due to ionization for protons and electrons in aluminum and lead.

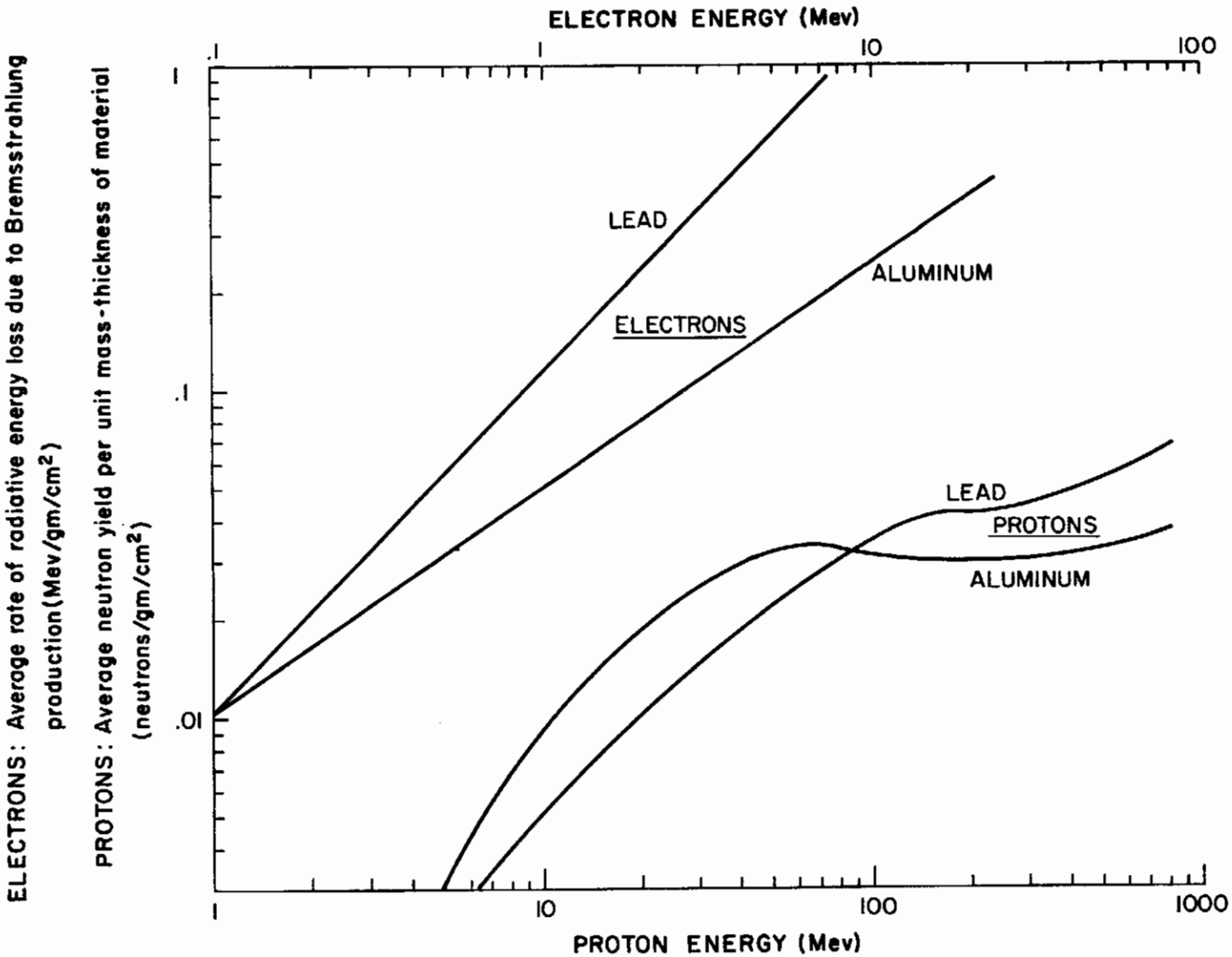

Figure 83. Radiation loss for electrons in aluminum and lead and neutron production for protons in aluminum and lead.

the known cross sections for reaction of the primary radiations with the various materials in the vehicle wall. These reaction cross sections of interest include those for production of secondary particles, bremsstrahlung, activation, excitation, etc. Presently, much of the available information concerning the spatial and spectral distribution of some of the space radiation fields is sketchy. The same is true for some of the reaction cross section data. The availability of some of this missing information will facilitate a better selection of orbits, trajectories, vehicle configurations, and the necessary shielding needed to minimize the radiation hazards to an astronaut for a specific space mission. Once the desired trajectory or orbit and the vehicle wall material and configuration are established, then the absorbed energy dose rates and total doses can be determined for the degraded radiation spectra inside the vehicle. The biological hazard in terms of dose can be established only after biological experimentation establishes the Relative Biological Effectiveness (RBE) of each type of space radiation as a function of radiation energy. Finally, the amount of protection that must be provided in the form of material shielding can be established for a given space vehicle mission only after acceptable RBE-corrected dose limits are determined.

If spacecraft weight were not a problem, the interior of the vehicle could be sufficiently shielded so that the radiation environment in the vehicle crew compartment would be very similar to the terrestrial radiation environment on earth. However, since the vehicle's payload weight is limited by the maximum thrust available in the booster rocket, any unnecessary excess shielding weight contained as a result of conservative estimates of shielding protection will impose performance limitations as well as detracting from the primary objective of the spacecraft. Therefore, it is important to obtain as accurately as possible the exact minimal amount of shielding necessary to protect against the radiation environments to be encountered during the flight mission.

Protons

To determine the dose rates and total doses inside a given manned space vehicle for a given trajectory or orbit for the space radiation field of category (2), one must consider the fact that a fraction of incident particles penetrate the vehicle walls at slant angles of incidence, thereby experiencing an effective shielding thickness greater than the actual wall thickness. In order to take into account this phenomenon, one must determine an effective thickness of the vehicle from the geometry of the vehicle. This will be a function of the incident particle energy and the angular distribution of the incident particles. However, for the purpose of present dose-rate calculations, the vehicle wall can be considered as a

small slab of material of a known thickness, where the incident isotropically distributed radiation of some known energy distribution is incident normally on the slab. By mathematical calculation the results thus obtained can be converted into those that would be obtained for a specific vehicle geometry of configuration. The error involved in not considering slant incidence amounts to not more than 10 to 15 percent.[5] Once values of primary particle spectra and the radiobiological response of tissue to these various radiations are known accurately, then more exacting calculations, taking into account particle penetration at slant angles, will be feasible. Until improved input data are obtained, refined calculations such as those for slant ranges are not realistic.

Account must be taken of both particle energy reduction through ionization losses and particle flux reduction as a result of removal type nuclear reactions. The dose rate delivered to the occupants of a space vehicle as a result of a vehicle's passage through a particular proton radiation field in space during a specific mission is a function of the following parameters:

(A) The energy spectrum of the primary proton radiation fields incident on the space vehicle throughout the vehicle's flight;

(B) The energy deposition rate in tissue for the degraded proton spectrum inside the vehicle;

(C) The nuclear reaction attenuation function for the incident protons in passing through the wall materials of the vehicle;

(D) The vehicle's configuration (sphere, cylinder, truncated cone, etc.) since the incident radiation is usually distributed isotropically over the entire vehicle surface.

In considering parameter (A), the equation of the incident proton energy spectrum is of the form:

$$CE^{-n} \quad ,$$

where, for Van Allen belt protons, the constants, C and n, are time dependent expressions that vary depending upon the vehicle's trajectory or orbit in its passage through the belt. For galactic cosmic rays, C and n are constants that depend upon whether the solar activity is maximum or minimum. For solar proton outbursts the energy spectrum is of the form:

$$CE^{-n}\, t_d^{-a} \quad ,$$

where C and n are constants depending upon the magnitude of the outbursts and where t_d is the elapsed time since the arrival of the maximum proton flux at the vehicle.

In order to evaluate parameter (B), the energy deposition rate in tissue, one must first determine the degraded energy spectrum of protons after they pass through the various materials of the space vehicle walls. By the use of the range versus energy tables (mean proton range in a material versus proton energy) and the stopping power data (energy loss per unit distance in a material), as contained in references 6 through 13, the residual energy of a proton of a given initial energy can be determined after passing through the materials of the vehicle walls. The same can be determined by integrating the proton energy loss rate equation of Bethe-Bloch over the vehicle wall thicknesses and substracting it from the original proton energy. Either method will yield the required degraded proton energy spectrum inside the space vehicle with fair accuracy. Detailed examples of determining the degraded proton energy spectrum through various materials are shown in references 14 through 17. Once the degraded proton energy spectrum inside the space vehicle has been determined for a specific vehicle mission, one can determine parameter (B) for type of dose rate or dose of interest.

Data for dE/dx in tissue are given in "Radiation Dosimetry" by Hine and Brownell.[18] Figure 84 shows the approximate amount of energy per proton absorbed by a "standard man" volume of tissue as a function of proton energy.[3]

Parameter (C), the incident proton nuclear reaction attenuation factor, which includes such nuclear reactions as (p, n), (p, γ), (p, α), (p, star), etc., is a function of the macroscopic proton reaction cross section, $\Sigma(E_p)$, and the thickness of the material. Values of $\Sigma(E_p)$, as a function of proton energy, are to be found in various references (10 and 19 through 23). As a general rule, the total macroscopic proton reaction cross section is relatively independent of proton energy for $E_p \geq 100$ Mev, and can be expressed by:[24]

$$\Sigma_T(E_p) = 0.0432\ \rho\ A^{-1/3} \quad ,$$

where ρ is the density in gm/cm^3 of a material of atomic weight A.

The total proton dose received by the occupants of the space vehicle throughout the total residence in space is obtained by integrating

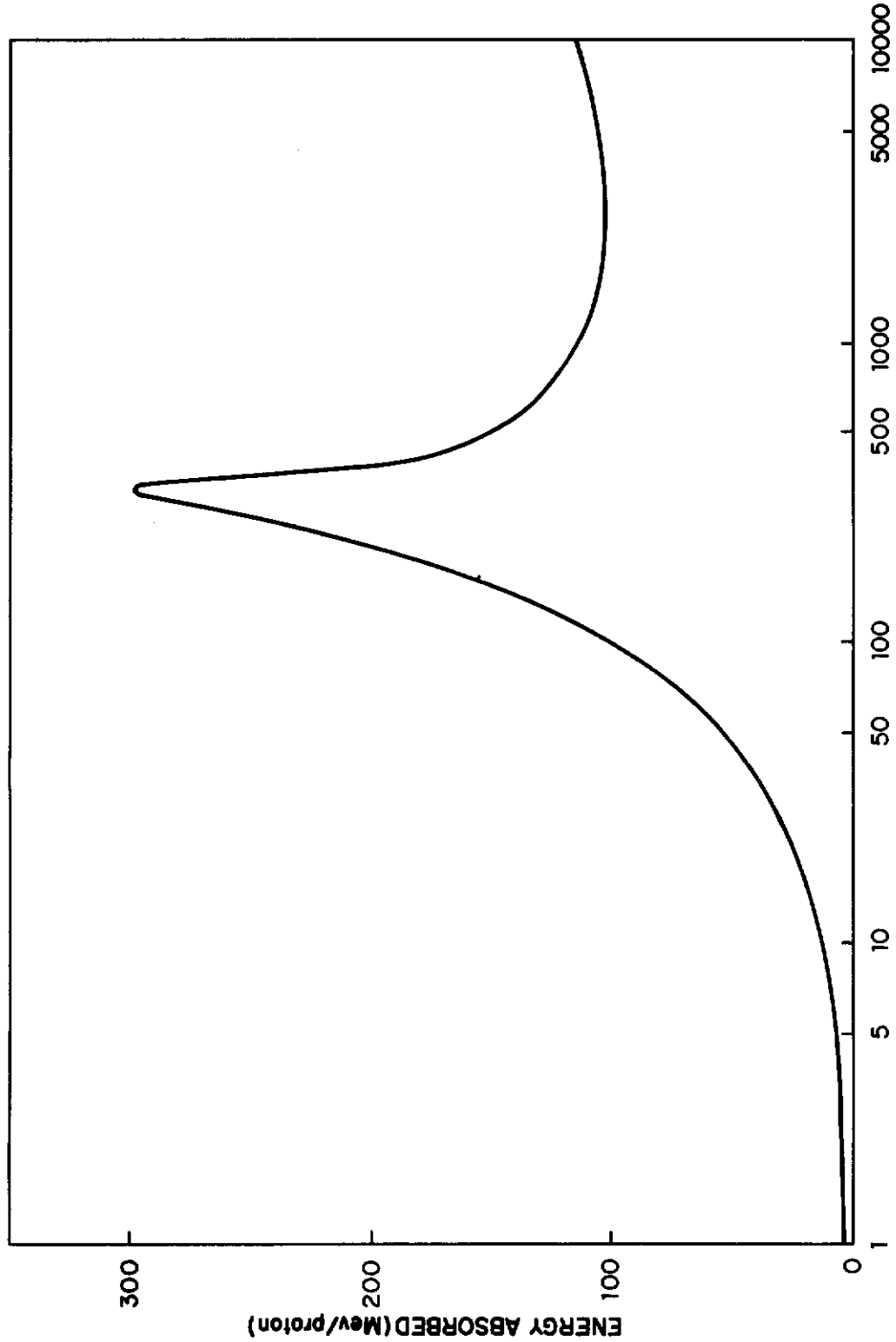

Figure 84. Total energy absorbed per proton by a volume of tissue equal to the thickness (50 cm) of an "Average Man".

the proton dose rate delivered to the occupants inside the space vehicle over the total time of the mission.

Examples of proton dose rate calculation using simplified assumptions of the incident proton energy spectra, vehicle configuration, and composition are developed in References 4, 5, 15, and 16. Programs are in progress to determine accurately, within the limits of available data, the dose rates to which astronauts would be exposed in specific vehicles for specific space missions. In some cases, electronic computers are being used to great advantage for these calculations.

Electrons

Since electrons of the energies involved in the space radiation (predominantly Van Allen belt electrons of category (1) with energies less than a few Mev) are quite easily stopped in a few millimeters of matter, they present a significant radiation hazard only through the production of secondary bremsstrahlung radiation. The electron fluxes of the Van Allen belt are quite high, and as a result, the bremsstrahlung flux will also be quite high if materials of high atomic number are used in the vehicle walls. Since these photons have a relatively high penetrating power, these secondary radiations could present a formidable hazard to space vehicle occupants. The production of bremsstrahlung radiation will be considered in the section on secondary produced radiations.

Primary Electromagnetic Radiation

The primary electromagnetic radiation above the earth's atmosphere, which includes soft x-rays and ultraviolet radiation, is of such an intensity and energy distribution as to be easily shielded by almost any vehicle wall thickness. As a result, this type of extraterrestrial radiation should comprise a minimal hazard.

Primary Neutrons

Available information indicates that no neutrons are present in the primary radiation, and that the neutrons that are detected outside the earth's atmosphere are those produced by cosmic ray primaries colliding with atmospheric nuclei. These are commonly, but technically incorectly, referred to as "albedo" neutrons. The present assessment of this neutron flux in and outside the earth's atmosphere is that it is of such a small value that no hazard is expected, and consequently no shielding of neutron radiation from this source should be required.

Heavy Nuclei Interaction

One of the space radiation effects that is frequently neglected in radiobiological studies is the localized cellular damage delivered to tissue cells by the traversal of a heavy nuclei at maximum ionization (so-called thin-down hits).

The effectiveness of particulate radiation in producing tissue damage is not dependent wholly upon the particle energy. It also depends on ionization intensity along the path of the particle in tissue. A measure of the intensity of the ionization is the linear energy transfer (LET) of the particle. The thin-down section of the particle track, near its termination, is the region of most intense ionization and the LET may surpass 10,000 ion pairs per micron of tissue. This portion of a particle track is considered to be the most effective for producing tissue damage.[1] Of the ambient space radiation, the particles that have the highest values of LET are the heavy nuclei ($Z \geq 2$) associated with category (3) of the primary cosmic radiation. Although the fluxes of these heavy nuclei are quite low, many feel that the amount of localized cellular damage, as a result of a thin-down hit delivered to some critical body organ such as the retina, brain, or other organ controlling a body function can cause serious impairment of function. Therefore, from the standpoint of manned space flight, it is important to study and determine the biological effects of irradiation by heavy nuclei.

Not until the RBE factors are determined as a function of LET, for all the biological responses of interest, can one ascertain the amount of biological damage delivered to a body organ of interest as a result of thin-down hits. When these biological uncertainties of heavy nuclei are resolved, a determination can be made of the necessary shielding, total or localized, that is required for protection.

SECONDARY RADIATIONS

In any complete analysis of the dose from any ambient radiation, one must consider the contributions of secondary produced radiations that are caused by the interactions of the incident radiation with the stopping medium. The sources of secondary radiation of predominant concern are the emission of high energy photons (bremsstrahlung) by electronic interactions and the emission of secondary particles, predominantly neutrons and protons as a result of interactions with atomic nuclei of the stopping medium.

Nuclear Reactions

The primary protons of the ambient space radiation are the major contributors to the nuclear reactions which include such possible

reactions as (p, γ), (p, p), (p, α), (p, n), (p, 2n), etc. These various reactions depend upon the incident proton energy and the nuclear properties of the target nuclei. Among the possible reactions listed, those that yield secondary neutrons will probably present the greatest potential hazard as far as proton secondaries are concerned.

The magnitude of the dose rate in a space vehicle's crew compartment due to secondary neutrons produced in the walls of the vehicle as a result of proton interactions from the space radiation fields of category (2) during a specific space mission is a function of the following parameters:

(A) The energy spectrum of the primary proton radiation fields incident upon the vehicle (the same parameter as that used in considering the primary proton dose rate in the vehicle).

(B) All of the possible neutron-yielding primary proton reactions with the materials of the vehicle wall.

(C) The neutron attenuation and/or moderation function.

(D) The flux-to-dose conversion factor for neutrons.

(E) The vehicle's configuration since the secondary neutrons are produced over the vehicle's entire volume.

To be considered in parameter (B), the possible neutron-yielding reactions, are both the prompt and delayed neutrons that are emitted with an isotropic distribution in the laboratory system of coordinates, as a result of proton interactions with a nuclei of vehicle wall materials. The cross sections involving these proton-neutron reactions, as well as other proton reactions, are available in the literature.[19,21,22,27]

The neutron attenuation function of parameter (C) involves the absorption of a neutron as a result of a nuclear reaction with atoms of the wall materials. The neutron energy moderation function involves the reduction of the neutron's energy as a result of elastic scattering events with the materials of the vehicle wall. The neutron absorption and scattering cross sections for various materials is given in reference 28.

An example of parameter (D), the flux-to-dose conversion factor for neutrons as a function of neutron energy, is shown in Figure 85.[29]

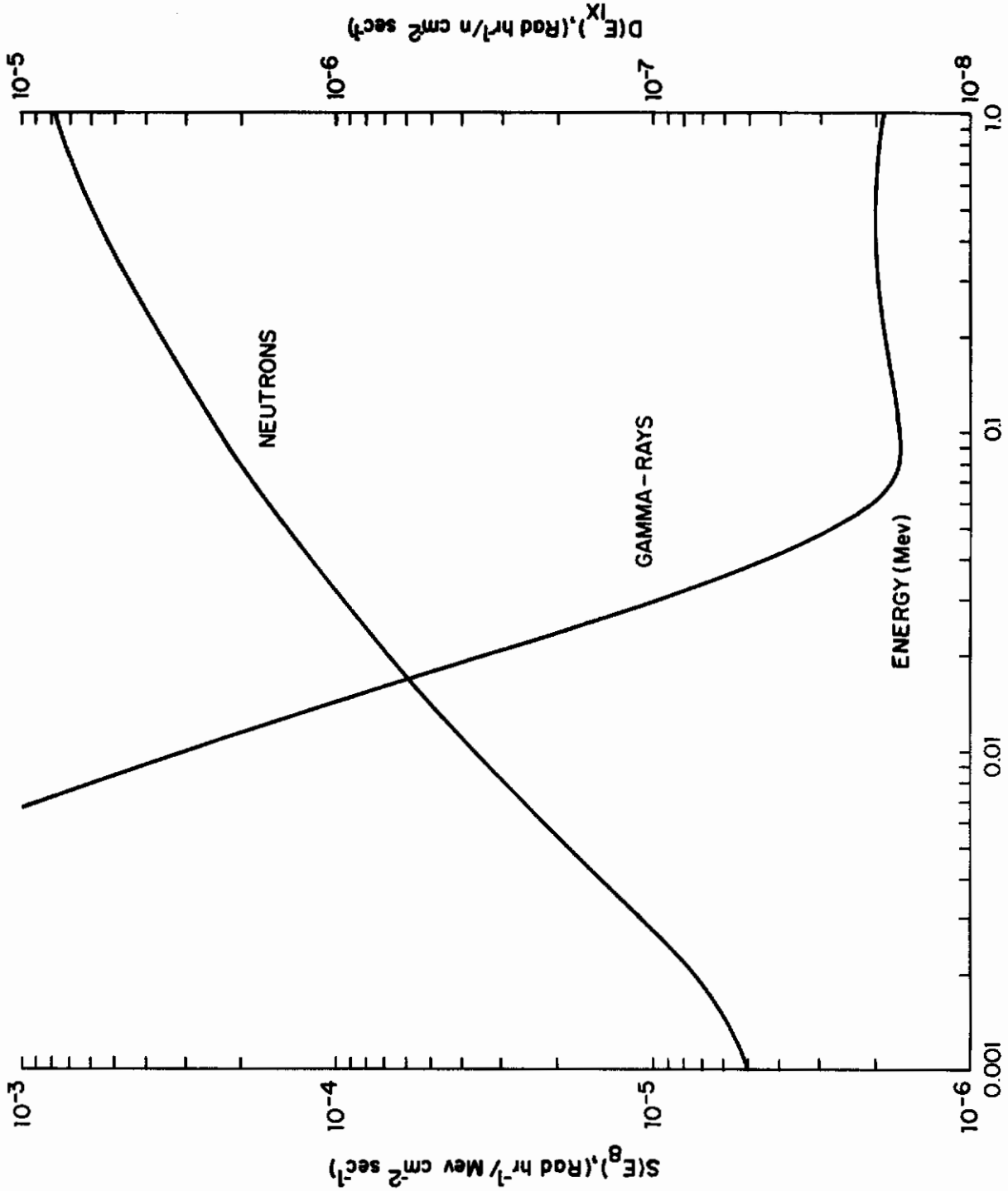

Figure 85. Gamma and neutron flux-to-dose conversion factors.

The total secondary neutron dose delivered to an occupant of the space vehicle then would be obtained by integrating the neutron dose rate over the total time of the vehicle flight.

By a similar type of determination, one could also obtain the dose rate and total dose inside a space vehicle from other secondary produced particles, such as secondary protons, alpha particles, etc., as a result of primary proton interaction with the wall materials of the space vehicle.

Bremsstrahlung

The major contribution to the production of bremsstrahlung radiation is the high intensity electron flux of the outer Van Allen belt. Most of the electrons that are incident on the vehicle will probably be attenuated or stopped in the first layer of the vehicle shell. Therefore, the resulting bremsstrahlung can be considered to originate at the vehicle surface. Since the incident electrons are considered to be isotropically distributed, the resulting bremsstrahlung will be isotropically distributed over the vehicle surface.

If not all the electrons are stopped in the first layer of the vehicle shell, the spectrum of those that do penetrate can be obtained from the original spectrum by use of the range-energy tables as previously established for protons. As a result, one would have a spectral distribution of electrons that are incident on the first layer of the vehicle wall and a spectral distribution for those that are incident on the second layer, etc. Hence, it can be considered that there will be two or more sources of bremsstrahlung that must be considered; one resulting from those electrons absorbed in the first layer of the vehicle and others resulting from those electrons that are absorbed in the subsequent layers of the vehicle wall. The magnitude of bremsstrahlung dose rate inside a spacecraft due to the degradation of electrons in the walls of the vehicle resulting from passage through the belt is a function of the following parameters:

(A) The spectral distribution of the emitted bremsstrahlung.

(B) The "build-up factor" for photons that penetrate the vehicle wall.

(C) The flux-to-dose conversion factor for photons.

(D) The photon attenuation function.

(E) The vehicle's configuration since the photon bremsstrahlung is produced over the entire vehicle's surface.

The spectral distribution of the emitted bremsstrahlung of parameter (A) is a function of: the atomic number and weight of the stopping material; the bremsstrahlung production cross section (these values for various materials can be found in the literature[30]); the electron stopping power of the shielding material (formulae and values for various materials are also available[31,32]); and a function of the energy spectrum of the incident electron radiation field which is an expression of the form:

$$CE^{-n} ,$$

where C and n are time dependent quantities which vary depending upon the vehicle's trajectory or orbit in its passage through the electron belt.

The photon "build-up factor" of parameter (B) in a material is the amount of increase in the intensity of the photon radiation as a result of secondary photons produced by primary photon interactions with the stopping material. Build-up factor values for various thicknesses of materials are available in nuclear literature.[31,32] Values of the flux-to-dose conversion factors for photons, parameter (C), as a function of photon energy, are shown in Figure 85[33]. The photon attenuation factor of parameter (D) is a function of the absorption coefficient for photons and the thickness of the material. Values of the photon absorption coefficient as a function of photon energy can be found in references 31 and 32.

Again, as with the proton total dose, the total dose delivered inside a space vehicle due to bremsstrahlung radiation would be obtained by the integration of the dose rate equation over the total time of the vehicle's flight.

A somewhat similar determination, as that above, can be employed to obtain the production of bremsstrahlung by the incident proton radiation fields in space.

Sample calculations are developed in references 4, 5, 15, and 16 for bremsstrahlung and secondary neutron dose rates using simplified assumptions as to the incident space radiation energy spectra.

Induced Radioactivity

When high energy particles interact with certain atoms of a material, certain radioactive isotopes are formed. Experiments carried out

with the Discoverer satellite series indicate that a number of induced radioactive isotopes, such as tritium, carbon^{14}, etc., are produced as a result of Van Allen belt protons and solar flare proton interaction with the materials of the space vehicle. It might be possible, though unlikely, that the production of certain radioactive isotopes could be high enough so that the quantities might approach biologically hazardous proportions. Therefore, for a given space vehicle configuration, a radioactivity production calculation should be assessed along with the direct shielding calculations to determine if the radioactivity induced within the crew compartment of the space vehicle would approach a hazardous level.

For the simplified case of a thin target, one can determine the rate of production of radioactive atoms, N_A, produced as a result of a flux of protons, D_P, incident on the target containing N_B atoms of a certain material by:

$$N_A = D_P \sigma_B N_B ,$$

where σ_B is the microscopic cross section for producing the radioactive atoms N_A. The rate of production is not as important as the rate of decay, and the rate of decay depends on the half life of the induced radioisotope. The rate of decay of the induced activity equals the rate of production, for practical purposes, if the period of irradiation is greater than six times the half life of the radioisotope. The given calculation assumes that the material is very thin and that there is no attenuation of the primary radiation. If, as a result of such calculations, considering all the material in the vehicle to be in a thin foil, it were found that the production rate of some specific radioactive isotope approaches a hazardous level, then more exacting calculations might be made to assess the problem more accurately and to determine procedures to be taken to alleviate the problem.

Shielding Requirements

Before one can design a detailed shielding system for a specific manned space vehicle or mission, "acceptable risk" radiation dose rates and integrated doses must be established. The task for the radiobiologist is not an easy one in that he is faced with space radiation fields about which little biological effects information is known. Since a single highly ionizing particle "hit" may possibly cause permanent tissue damage, and since these space radiation environments are not easily simulated in the laboratory, the establishment of these standards is most difficult. The RBE factors which must be determined for each type of radiation as a function of particle energy are not even firmly established for nuclear radiations commonly encountered in earth-bound endeavors.

Shielding Methods

It has been established that protons of the space radiation environment present the most serious radiation problem to the astronaut. Shielding will definitely be required, and since the shielding deals primarily with charged particles, there are two methods which could be used: (1) "active shielding"--causing the trajectories of the incident charged particles to be altered in such a manner that they do not enter the space vehicle; or (2) "passive shielding"--causing the incident radiation to be absorbed so as not to enter the vehicle.

Concerning the first method, active shielding, deflection of incoming charged particles can be accomplished by the use of either electrostatic or electromagnetic fields. To create a magnetic field of such a magnitude as to deflect adequately high-energy charged particles by ordinary methods would require an enormous amount of power. The weight of equipment required to produce this power will be of such a value as to make it almost infeasible to carry in a space vehicle. However, proposed ideas based on superconductivity are being investigated as possible means of reducing power requirements. Another scheme which appears to have merit, based on the fact that the vacuum in space is such a perfect insulator, is the employment of electrostatic charge built up on the surface of the space vehicle. The actual power required to maintain such a charge would be primarily that needed to replace losses due to leakage currents. Actual development of a workable generator and elimination of other problems such as arcing and communication problems, probably entails some very serious difficulties. The magnitude of the electrostatic charge required to reject a proton approaching a spherical body from an infinite distance with a known kinetic energy is obtained by integrating the Coulomb force field equation and obtaining:[34]

$$E = 300\ Q/R \quad ,$$

where E is the kinetic energy of the particle in ev, Q is the charge on the sphere in statcoulombs, and R is the radius of the sphere in centimeters. Now the potential at the surface of a sphere is given by:

$$V = 300\ Q/R \quad ,$$

where V is in volts. Therefore, V = E, or the rejection potential in volts is equal to the incoming particle energy in electron volts. As an example, in order that a body would not be struck by any incoming protons with energies of 200 Mev or less, the body must be given a charge of 200 million volts. With adequate insulation such potentials are feasible. Though the

problems involved seem extensive, this method of electrostatic shielding certainly deserves further investigation.

Passive shielding is defined as the use of inert material or a composite of materials to absorb or attenuate the incident radiations. From the standpoint of shielding materials, weight is easily the most important factor in determining the best shield materials for manned space vehicles. All materials of low atomic number, such as hydrogen, hydrogenous compounds, carbon, etc., are superior in primary shielding protection against protons, because of their large stopping power for charged particles and their relatively low yields for the production of nuclear reactions and bremsstrahlung. Beryllium, magnesium, and aluminum are slightly less effective than the hydrogenous materials, but the differences are not so great when one considers their advantages in terms of engineering properties. If secondary produced radiation is high, a secondary shield will be necessary. That is, if the intensity of the secondary produced neutrons is high, then these neutrons might be moderated by the low-Z primary shield and absorbed by a thin inner secondary shield of some high neutron cross section material (cadmium, boron, lithium, etc.). Bremsstrahlung radiation of relatively low energy can be absorbed easily by a small amount of high-Z material. In general, then, the amount of shielding necessary for radiation protection is dependent upon the specific vehicle mission, its configuration, and the astronaut's radiation exposure limitations.

Shielding Reduction Concepts

Since the ambient space radiations are generally considered to be isotropically distributed, a total radiation shield will be needed for protection. The addition of this nonpayload weight will naturally reduce the overall utility of the vehicle and possibly render some missions impractical. Therefore, it is important that the utmost effort be expended to ascertain the optimum amount of material that must be added to the vehicle for shielding.

Because of their limitation to the vicinity of the earth, it is evident that the Van Allen radiation belts are problems only for manned missions which must operate in orbits which carry the vehicle within these bands. Of course, operations carried on within these belts for extended periods will require special radiation shielding. Missions that carry man into interplanetary space probably will traverse the region of Van Allen radiation quite rapidly, thereby keeping the exposure time low, or they can by-pass these bands entirely by using the polar escape routes. The principal factor dictating the shielding requirement in interplanetary space will be solar proton outbursts. If solar proton event prediction methods

are perfected, and the Van Allen radiation fields are "skirted" via the polar escape routes, a mission may be completed in a short duration (less than a week) with little or no additional radiation shielding and with a minimum of risk. For long-endurance space missions, solar protons will certainly create a radiation hazard. However, the fact that the solar proton outbursts are intermittent and infrequent in nature suggests that a weight advantage can be realized by the concept of an emergency crew compartment. In this plan, one compartment would be used for normal operations, and the other much smaller, heavily shielded compartment would be used for short-interval occupancy during solar flare events.

In addition, strategic placement of equipment and stores on board the vehicle in order to be effective as shielding should also be an important means of reducing nonpayload shield weight.

Vehicles having either nuclear auxiliary power units or nuclear propulsion units present an additional shielding problem since a powerful source of radiation will be carried on board in proximity to the crew. In the vacuum of space, the shielding of the crew compartment from reactor radiation will involve little more than the use of a shadow shield since no air scattering component will be involved. The shadow shield can be placed near the reactor or can be incorporated into the shield surrounding the crew compartment and thus act as a shield against the natural radiation environment as well as that from the reactor. Considering the two-compartment concept, the small, heavily shielded compartment might be placed between the reactor and the larger crew compartment. The small crew compartment then would serve doubly as a shadow shield between the reactor and the large normal crew compartment. In the event of a solar flare, the reactor could be shut down to make the small compartment safe for occupancy.

Another method is to mount the nuclear power unit on extendable supports so that the unit could be extended a distance ahead or behind the vehicle, making use of the inverse square law in protecting against the reactor radiations. Combinations of these methods, as applicable, will probably be used in an optimum design.

In regard to radiation protection standards associated with the maximum permissible level of radiation exposure, it is important from the standpoint of shielding weight requirements that space radiation exposure limitations be set realistically. Limitations established for industrial radiation protection standards are based on life-time radiation exposures. Certainly these exposure levels, from the standpoint of radiation risk in space exploration, are too conservative and can result only

in undue major engineering problems. It may prove possible, through radiobiological experimentation and agreement on risk relative to the importance of space exploration, that a new space radiation protection standard can be established. Certainly, establishing higher tolerable exposure levels will help to alleviate some of the practically insuperable engineering problems of manned space flight.

SECTION VII

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EXPLANATION OF TERMS

Alpha Particle - α

A form of particulate radiation with properties identical to those of a helium nucleus (consisting of two protons and two neutrons) usually considered as a particle emitted from the nucleus of certain radioactive isotopes in the process of decay of disintegration.

Angstrom - $\mathring{A}$

A unit of wavelength or distance (equal to 10^{-8} cm).

Astronomical Unit - A.U.

The average distance between the earth and the sun. Though not known precisely it has a value of about 1.496×10^{8} kilometers or 9.2897×10^{7} miles.

Atomic Number - Z

The number of protons in the nucleus of an element.

Beta Particle - β

A charged particle emitted from the nucleus of an atom having a rest mass and charge equal in magnitude to that of the electron. Normally β or β^{-} refer to such particles with a negative charge, and β^{+} refers to those with positive charges and are often termed positrons.

Bremsstrahlung

Bremsstrahlung is the production of electromagnetic radiation (photons) by the acceleration (positive or negative) that a fast, charged particle (usually an electron) undergoes from the effect of an electric or magnetic field; for instance, from the field of another charged particle (usually a nucleus). The spectral distribution is continuous; the well-known continuous X-radiation being a prominent example.

Chromosphere

The region of solar atmosphere surrounding the photosphere. It blends into the corona.

Corona

The rarified atmosphere of the sun which extends into interplanetary space.

Cosmic Rays - Primary

High energy particulate radiation originating outside the earth's atmosphere composed of ~85% protons, ~13% alpha particles, and the remainder nuclei of heavy elements.

Cross Section

The probability that one incident particle will suffer a specified interaction while passing through a foil of material containing one target atom per unit foil area.

Cutoff Energy

The value of energy of a primary particle below which it will be incapable of penetrating a medium, such as a magnetic field or material thickness.

Dipole Magnetic Field

The magnetic field which can be represented as one arising from two separated magnetic poles of equal strength and opposite sign. The geomagnetic field is a dipole field to a first approximation.

Dosimeter

An instrument for measuring an accumulated radiation dose (contraction of dose meter).

Ecliptic Plane

The ecliptic plane is that plane which is coincident with the earth's orbit about the sun (the plane of the earth's equator is inclined 23° 17' to the ecliptic plane).

Electron

Negatively charged particle which is a constituent of every neutral atom.

Electrostatic Unit of Charge - esu

The unit of charge in the "electrostatic system of units". 3×10^9 esu of charge = 1 couloumb. 2.08×10^9 electric charges = 1 esu of charge.

Electron Volt - ev

A unit of energy equal to that of an electron after falling through a potential difference of one volt. (1.602×10^{-12} ergs) 1 kev = 10^3 ev; 1 Mev = 10^6 ev; 1 Bev = 10^9 ev.

Erg

The unit of energy in the cgs (centimeter-gram-second) system of units (equivalent to one dyne-centimeter of work). Approximately 0.624×10^{12} ev = 1 erg.

Fast Neutron

A neutron with energy in excess of 0.1 Mev.

Fission Fragments

The particles resulting from exothermic splitting of atomic nuclei.

Galactic Cosmic Rays

Those cosmic rays which originate from sources outside the solar system.

Gamma Rays - γ

Electromagnetic radiation of short wavelengths originating from within the nucleus of an atom which distinguishes them from x-rays which are considered as originating outside the atomic nucleus.

Genetic Damage

Damage to the genes of chromosomes which results in changes in characteristics that are transmitted to offspring.

Half Life

The time interval for the total number of atoms of a particular radioactive isotope to be reduced to exactly one-half the original number; or, referring to a single particle or atom, the time interval required for the probability of disintegration to reach the value of 0.5.

Heavy Nuclei (or Primary Radiation)

Those atomic nuclei of galactic or solar origin with a charge greater than or equal to 2.

Ionized Atom

An atom which has lost or gained one or more orbital electrons, thus causing the atom to become charged.

Ionizing Radiation

Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

Isotope

Atoms of an element having the same number of protons, but different numbers of neutrons in the nucleus.

Isotropic

Those quantities which have the same properties in all directions.

Limb (Solar)

The outer edge of the sun's disk.

Linear Energy Transfer - LET

The linear rate of loss of energy (locally absorbed) by an ionizing particle traversing a material medium (usually expressed in units of kev/micron of material).

Magnetic Rigidity

A measure of the momentum of a particle which determines the ability of a high energy charged particle to penetrate a particular magnetic field. A measure of the magnetic rigidity in the particle's energy divided by its charge.

Mass Number - A

The total number of protons and neutrons in a nucleus giving the approximate measure of the nuclear mass or atomic weight.

Mass Stopping Power

The loss of energy per unit mass per unit area by an ionizing particle traversing a material medium.

Mean Free Path - MFP

The average distance traveled by a particle between two consecutive collisions with atoms or molecules.

Median Lethal Dose - LD_{50}, LD_{50-30}

Radiation dose which would be expected to be lethal to 50 percent of the exposed biological entities or individuals (within 30 days when written LD_{50-30}).

Meson

A particle of secondary cosmic ray origin carrying either a positive, negative, or no charge. The rest mass is variable and is expressed in multiples of the mass of an electron.

Meteorite

Those meteoroids which can survive passage through the earth's atmosphere.

Meteoroid

Any material particle, or small body, of extraterrestrial origin.

Micrometeorite

These meteoroids with a diameter less than approximately 100 microns.

Micron - μ

A unit of distance equal to 10^4 Å or 10^{-6} meters.

Mirror Points

The location near the magnetic poles on lines of force at which spiraling electrons under the influence of the field are reflected back along the lines of force.

Mutant

A living organism with inherited characteristics differing from its parents due to a change in genetic structure.

Neutron

An elementary nuclear particle, electrically neutral, mass of 1.008986 mass units.

Nova

A star which rapidly increases in brightness, then gradually subsides.

Nucleons

Parts of atomic nuclei--protons and neutrons.

Nucleus

That portion of an atom in which the total positive electric charge and most of the mass are concentrated.

Omnidirectional Intensity

That measured intensity which takes into account particles incident from all directions in space.

Particle Scattering

The change in direction of an incident particle as a result of a collision or interaction with matter.

Particulate Radiation

Ions, atoms, and subatomic particles with energy sufficient to penetrate a significant thickness of matter.

Penumbra

The filamentary structure surrounding a sunspot of intermediate brightness between the photosphere and the dark part of the spot (umbra).

Photon

A quantum of electromagnetic energy. That is, a quantity of energy emitted in the form of electromagnetic radiation such as radiowaves, light, x-rays, and gamma rays.

Photosphere

The layer of gas surrounding the sun which is visible. Often referred to (technically incorrectly) as the visible surface of the sun.

Plasma

Highly ionized body of gas in which the over-all electrical charge is essentially zero.

Primary Radiation

Naturally occurring extraterrestrial radiation which has not undergone collision or absorption in matter.

Proton

Elementary nuclear particles with a unit positive electric charge equal numerically to the charge of the electron, but with a mass roughly 1840 times the mass of an electron.

Proton Event

An outburst of solar protons from a flare region which projects into space causing an increase in the radiation background.

Quantum Transition

The change of an orbital electron from one shell to another accompanied by an emission or absorption of energy.

Rad - Radiation Absorbed Dose

The unit of absorbed dose, which is 100 ergs per gram in the medium of interest. When ionizing radiation imparts 100 ergs of energy per gram of material to a material, it is said to have received a one rad dose. Thus, the absorbed dose in rads is the absorbed dose in ergs divided by 100. If a radiation field is to be characterized by the dose rate in rads per unit time, then the material in which the energy absorption is taking place must be specified, such as rads-carbon/hr.

Radiation

Energy of electromagnetic form or particulate matter.

Radiation Sickness

A syndrome following intense acute exposure to ionizing radiation. It is characterized a few hours after exposure by nausea and vomiting with other symptoms following; the same symptoms may occur in time after chronic exposure to high levels of ionizing radiation.

Radiobiology

The study of the effects of ionizing radiation on biological systems.

REL - Rate of Energy Loss

The rate of energy loss by a high-energy particle along its track as it passes through a medium. Equivalent to the energy absorbed from a single high-energy particle in unit thickness of a material. It is equivalent to linear energy transfer (LET).

Relative Biological Effectiveness - RBE

Biological potency of one radiation as compared with another. It is numerically equal to the inverse of the ratio of absorbed doses of the two radiations required to produce equal biological effect. The reference radiation is often 200 kv x-rays.

Relativistic Velocity

A velocity which is a significant fraction of that of light so that the quantity $(1 - v^2/c^2)$ cannot be treated as unity (v = velocity, c = velocity of light).

Roentgen

The unit of exposure dose of x- or gamma radiation and is defined as "the quantity of x- or gamma radiation such that the associated corpuscular emission per 0.001293 grams of air produces, in air, ions carrying one electrostatic unit of electricity of either sign.

Roentgen Equivalent Man - REM

The unit of biological damage or effect often referred to as the RBE dose. The quantity of any type of ionizing radiation when absorbed in man produces the same specific biological effect as the absorption by man of one roentgen of x- or gamma radiation of an energy of 200 kev. REM = RBE × Rad.

Roentgen Equivalent Physical - REP

The amount of any ionizing radiation which will result in the absorption in tissue of 93 ergs/gm.

Secondary Radiation

The particles and photons resulting from interactions of primary radiation with matter.

Solar Cosmic Rays

Those cosmic rays which originate from the sun; predominately protons.

Solar Cycle

The approximately eleven-year periodicity in activity of the sun; the number of sunspots being indicators of activity.

Solar Wind

The theoretical outflowing of ionized gas from the sun.

Solid Angle

A measure of the opening between surfaces which meet at a common point--i.e., cone, pyramid, etc. A three dimensional angle, the apex angle of a cone or pyramid. The unit of solid angle is the steradian.

Somatic Damage

Damage to the body itself.

Spectrum

A display, record, or plot of the distribution of the intensity of radiation of a given kind as a function of its energy, momentum, frequency, wavelength, or any other related quantity.

Spectrum (Differential)

The distribution in energy of a radiation field expressed in terms of the relative number or intensity of radiation per unit energy interval. For cosmic and Van Allen radiations the differential spectrum is often expressed as the relative number or intensity of particles per unit energy interval (between E and E + ΔE) passing through a unit area per unit time from a unit solid angle (number of particles/cm^2 sec ster).

Spectrum (Integral)

The relative distribution in energy of a radiation field expressed in terms of the intensity of the radiation with an energy

greater than a given value [F(>E)]. For cosmic and Van Allen radiation the integral spectrum is often expressed as the number of particles with an energy greater than a given value passing through a unit area per unit time from a unit solid angle (number of particles $E \geq E_1$ / cm^2 sec ster).

Star

The tracks made by ionizing particles originating from a common point as the result of a nuclear reaction. So named for the star shape of the tracks in photographic emulsions.

Steradian - Ster

The unit of measure for the solid angle subtended at a point by a surface. A surface completely surrounding a point subtends a solid angle of 4π steradians. (The solid angle in steradians, submitted by a surface at a point is its projected area on a sphere of unit radius with center at the point in question.)

Sunspot

A region on the sun which appears dark against the photosphere.

Supernova

A star of great mass (much more than the sun) which ejects into space excess ionized gaseous material.

Thermal Neutron

A neutron with velocity of approximately 2200 meters/sec or with energy of 0.025 ev.

Thin-Down

The densely ionized track of a particle as it loses all of its energy to its surroundings in a short path length. So called for the shape of the track which thins to a point at its terminal end.

Threshold Dose

The minimum dose that will produce a detectable degree of any given effect.

Umbra

The darkest part of a sunspot.

X-Rays

Penetrating electromagnetic radiations having wavelengths very much shorter than those of visible light. They are usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions it is customary to refer to photons originating in the nucleus as gamma rays, and to those originating in the extra-nuclear part of the atom as x-rays.