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SUMMARY OF PRESENT KNOWLEDGE ON SPACE RADIATION

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Abstract

In space there are various types of ionizing radiation which are known to exist. These radiations consist of protons, electrons, alphas, heavy nuclei, and X- and γ - rays. Neutrons have been postulated but not detected (this does not refer to albedo neutrons caused by primary cosmic ray particles interacting with planetary atmospheres).

There are four main categories of space radiation, namely interplanetary plasma, cosmic radiation, solar cosmic radiation, and Van Allen radiation (particles trapped in planetary magnetic fields). The existence of energetic charged particles in space has been known for about fifty years. However, only in the past decade have we been able to make observations away from the influence of the earth's magnetic field.

This paper will discuss the present knowledge of the nature and properties of interplanetary plasma, galactic, solar, and trapped radiations, ^{is discussed} Particular emphasis ^{is} ~~will~~ be placed upon solar cosmic radiation, solar flares, solar-terrestrial relationships, and time variations. Results of analyses of various events ^{is} ~~will~~ be described in light of biological dose restrictions. Present research programs on prediction of solar cosmic rays and their time variations ^{are} ~~will~~ also be discussed.

1.0 Introduction

The rapid advances in space science over the past few years have provided new knowledge of the nature and properties of space radiation. As new and better data becomes available, many existing concepts of the space environment will require revision. It is the intent of this paper to briefly summarize our present knowledge of space radiation. Because of the potential hazards of space radiation to manned space travel, an attempt has been made to discuss those properties which have bearing on biological and shielding problems and mission parameters.

1.1 The Nature and Properties of Space Radiation

In space there are various types of ionizing radiation which are of concern to manned space flight. These radiations consist of protons, electrons, alphas, heavy nuclei, and X- and γ - rays. Neutrons have been postulated but not detected (this does not refer to albedo neutrons caused by primary cosmic ray particles interacting with planetary atmospheres).

Protons constitute the greatest radiation hazard in space, although electrons are the primary concern in the outer regions of the magnetosphere (i.e., outer Van Allen zone). For purposes of simplicity, we will separate space radiation into four categories (1) interplanetary plasma, (2) galactic, (3) geomagnetically trapped, and (4) solar. In a complete treatise of radiation in space, it would be desirable to add another category, namely, long wavelength electromagnetic radiation (i.e., radio-wave emission from the sun and stars). However, as we are mainly concerned here with radiations which present biological problems, short wavelength electromagnetic and high energy particulate radiations will receive major attention.

1.11 Interplanetary Plasma

Parker's theoretical model of the "solar wind"¹ (outward flow of ionized hydrogen gas from the solar corona), which is based on observations of aurorae and oscillations of comet tails, predicts the following plasma properties:

Active Sun (sunspot maximum):	Density $10^4/\text{cm}^3$ at 1 A.U.
	Velocity 1500 km/sec
Quiet Sun (sunspot minimum):	Density $10^2/\text{cm}^3$ at 1 A.U.
	Velocity 500 km/sec.

Direct measurements of the "solar wind" properties have been made by the Explorer X and Lunik satellites and the Mariner II space probe. According to Neugebauer and Snyder ² from an analysis of Mariner II plasma probe data, the plasma flux is about $1.2 \times 10^8/\text{cm}^2/\text{sec}$, the plasma energy density is about $4.4 \times 10^{-9} \text{ erg/cm}^3$, and the velocity of the plasma is between 400 and 700 km/sec. These experimental values agree fairly well with Parker's prediction for solar minimum. As the energy of the plasma particles is very low (a few KeV for protons), there is no biological problem associated with the solar wind.

1.12 Galactic Cosmic Radiation

The existence of very energetic radiation in space has been known for almost 50 years. Since the original discovery, enumerable experimenters have made major contributions to the field of cosmic ray physics. Only within the last decade have scientists been able to investigate the nature and properties of cosmic rays away from the direct influences of the earth.

Galactic cosmic radiation consists mainly of very energetic nuclei stripped of their electrons. Electrons and gamma rays are also present, but are very minor constituents. The composition is well known and is approximately 84% protons, 14% alphas, 1% carbon, nitrogen, and oxygen, 0.25% in the group heavier than neon, 0.25% lithium, beryllium, and boron, and less than 1% high energy gammas and electrons. Recent space experiments, notably in OSO, Ranger III, and Ranger V, indicate that rather large fluxes of gamma rays may exist in space (the energy-spectra, origin and directionality are not yet known). Other recent experiments indicate that electrons may comprise up to 3% of the galactic cosmic ray composition³. It can also be inferred from existing data that the relative abundance of elements (excluding helium) normalized to hydrogen is probably not a constant ratio, but is slightly time and directional dependent. The hydrogen to helium ratio appears to be constant in time.

In regard to shielding problems, we are mainly concerned with the proton component. For purposes of defining flux, the values of 2.5 and 5 particles/cm²-sec (omnidirectional) are assumed for periods near sunspot maximum and minimum respectively.

The energy range of the galactic cosmic rays extends from tens of MeV up to at least 10^{12} MeV, the average energy being about 4000 MeV. Converting Waddington's value of the charge distribution above 4.5 Bv for a quiet solar period⁴ from unidirectional to omnidirectional flux we

have

$$\begin{aligned}
 J(\text{flux}) &= 0.7662 \pm .0377 \text{ protons/cm}^2 \text{ -sec} \\
 J &= 0.1105 \pm .0035 \text{ alphas/cm}^2 \text{ -sec} \\
 J &= 0.0019 \pm .0006 \text{ light nuclei } (3 < Z < 6)/\text{cm}^2 \text{ -sec} \\
 J &= 0.0072 \pm .0004 \text{ medium nuclei } (6 < Z < 10)/\text{cm}^2 \text{ -sec} \\
 J &= 0.0024 \pm .0003 \text{ heavy nuclei } (Z \geq 10)/\text{cm}^2 \text{ -sec} \\
 \text{total flux} &= 0.888 \pm .04 \text{ particles/cm}^2 \text{ -sec for } R \geq 4.5 \text{ Bv}
 \end{aligned}$$

As the measured total flux in space is between 2.5 and 5 part/cm² -sec, it is seen that the majority of the flux falls in the rigidity* region less than about 4.5 Bv.

The energy spectra of charged components in the galactic cosmic radiation, especially at high energies, is closely approximated by $J(E) = \frac{C_Z}{(1+E)^x}$ particles/M² -sec.sr with kinetic energy/nucleon $> E$, where x is a constant independent of the atomic number Z , and C_Z is a function of Z^5 . According to McDonald and Webber,⁶ the differential rigidity spectra of protons and alphas have the same form during the complete 11 year solar cycle, the total intensity is decreased by about a factor of 2 from solar minimum to solar maximum and the lower energy particles are affected most but not completely removed from the primary beam. Also, the solar and Forbush modulation of intensity appears to be identical for all positively charged particles.

* Rigidity is defined as the ratio of momentum to the charge, or $R = \frac{pc}{Ze}$, where p is the momentum (in units of Bev/c), c is the velocity of light, and Ze is the charge on the particle.

The time-variations of the properties of primary cosmic rays is perhaps one of the most interesting areas of cosmic ray physics. Many papers have been published which discuss the cause and nature of time-variations. In cosmic ray physics, there are six types of time-variations, namely, the 11-year variation, 27-day variation, Forbush decreases, diurnal variation, solar flare effect, and meteorological effects. Of these six only three apply to "space", i.e., the 11-year, 27-day, and Forbush decrease variations. (Although the sun occasionally produces particles of energies similar to that found in galactic cosmic rays, the particles are not a part of galactic cosmic radiation. Rather, these particles are included in the category of solar cosmic rays and will be discussed later). The mechanisms producing the three variations are the same.

The 11-year variation is linked directly with the solar cycle. In simple terminology, the sun's activity follows a periodic cycle of approximately 11 years. When the sun is most active, i.e., the number of sunspots reaches a maximum, the intensity of the galactic cosmic rays approaches minimum. The cause is attributed to a simple process whereby the sun, upon reaching maximum activity, produces a maximum amount of low energy corpuscles. This plasma, having a fairly high energy density, can carry with it solar magnetic field lines. Near sunspot maximum, the complete solar system may contain a very large amount of plasma. The magnetic field lines "frozen" or carried by the plasma as it moves away from the sun

influence the trajectories of galactic cosmic rays (particularly the low energy part of the spectrum). Some of the galactic cosmic rays are then excluded from the solar system. Near sunspot minimum when the sun is least active, very little plasma is being emitted, and the plasma which had occupied the solar system has since dispersed. The low energy component of the galactic flux, which suffered the largest modulation, then returns to normal, although it was never completely removed. The 11-year variation is by far the largest variation causing changes in total intensity of about a factor of 2.

The 27-day variation is attributed to long-lived active regions on the solar chromosphere. Complex active sunspot regions can produce almost a continuous outward flow of plasma. This plasma is most likely emitted radially from the sun and affects the low energy component of the primary beam in the same way as discussed above. The same region, if still active, may again produce a small decrease in the primary flux 27 days later, the rotational period of the sun. The 27-day effect is usually quite small.

A Forbush decrease is caused by the solar emission of an unusually dense plasma cloud. Usually a large Forbush decrease is preceded by a major solar flare and accompanied by a magnetic storm and other geomagnetic phenomena.

The three major variations in the intensity of galactic cosmic rays

in space can then be attributed to the same physical process, namely, modulation of the flux of the low energy particles by magnetic fields.

Galactic cosmic rays are essentially isotropic over 4π in space. However, there appear to be small anisotropies in some directions, although the variations are very small.

1.13 Geomagnetically Trapped Radiation

One of the most interesting results of the IGY was the discovery of a region of trapped corpuscular radiation around the earth. The initial detection of the trapped radiation was made by instrumentation on board Explorer I and Explorer III satellites ^{7,8} provided by the Cosmic Ray Group at the State University of Iowa led by Prof. J. A. Van Allen. These satellites were launched on February 1, 1958 and March 26, 1958. Although "Van Allen Radiation belts" initially referred to geomagnetically trapped radiation, the name has been used in a broader sense to apply to radiation trapped in any planetary magnetic field.

Geomagnetically trapped radiation consists of charged particles trapped in the earth's magnetic field. The particles exhibit three motions, namely, a circular motion about the field line, motion along the guiding center connecting the two mirror points, and longitudinal drift. There are three invariants which are used to theoretically

describe the motion of charged particles in the Van Allen belts ^{9,10}. The first invariant is the Adiabatic or Magnetic Moment Invariant. If the conditions are such that the magnetic field strength varies only slightly over the distance the particle moves in several cyclotron periods and in a time comparable to several cyclotron periods then the magnetic moment $1/2 M v_{\perp}^2/B$ or $W_{\perp}/B$ is a constant of the motion.

For charged particles in the earth's dipole field, the cyclotron radius is much smaller than the characteristic dimensions for appreciable changes in field strength and, except during magnetic storms, changes in the magnetic field are small in times the order of the cyclotron period. The requirements for the conservation of the magnetic moment are therefore well satisfied for charged particles in the earth's magnetic field.

The angle α between the particle velocity vector and the magnetic field direction is the pitch angle. From the First Invariant the magnetic moment is a constant.

$$\mu = \frac{W_{\perp}}{B} = \frac{W \sin^2 \alpha}{B} = \text{constant} \quad \text{Eq. (1)}$$

If there are no electric fields the total kinetic energy, W , is a constant. Then for a particle at two different positions (1) and (2)

as it moves along a line of force

$$\frac{\sin^2 \alpha_1}{B_1} = \frac{\sin^2 \alpha_2}{B_2} \quad \text{Eq. (2)}$$

where α_1 is the pitch angle of the particle at position 1 where the field is B_1 .

When the particle reaches the position where $\vec{V}$ is perpendicular to B ,

$$\sin^2 \alpha = 1 \quad \text{Eq. (3)}$$

and the particle has reached its mirror point or turning point.

The Second Invariant is the Integral or Longitudinal Invariant.

The integral

$$I = \oint v_{II} dl \quad \text{Eq. (4)}$$

of the velocity parallel to the field over a complete cycle (i.e., between mirror points) is also an adiabatic invariant. (dl is an element of length along the line of force). The quantity I is the action variable for the equation of motion parallel to the field line. This invariant places an additional constraint on the motion of the particle. A trapped particle drifting in the geomagnetic field so that I is constant, must return to the same field line after a complete circuit of the earth. A consequence of this is that the particle sweeps out a well defined integral or longitudinal invariant surface as it drifts around the earth.

The Third Invariant is the flux invariant

$$\phi = \int_S \vec{B} \cdot d\vec{s} \quad \text{Eq.(5)}$$

($d\vec{s}$ is an element of surface area). The magnetic flux inside the integral invariant surface discussed above is also an invariant. The third invariant is useful primarily in analyzing particle motions when the magnetic field is changing in time.

A complete description of the particle contents in the Van Allen belts may be expressed in terms of a set of seven-parameter functions:¹¹

$$j_1(r, \phi, \theta, \alpha, \beta, E, t) \quad \text{Eq.(6)}$$

where j_1 is the differential unidirectional intensity of particles of type 1 (i.e., electrons, protons, alpha particles, etc.); at a point r, ϕ, θ ; in the direction specified by angles α and β ; in unit range of energy at E ; and at some instant of time t .

Considering the quasi-stationary state of the trapped particles, the unidirectional intensity can be written as

$$j_1(\alpha_0, L, E) \quad \text{Eq.(7)}$$

where α_0 is the pitch angle at the equator on a magnetic shell whose equatorial crossing radius is L times the radius of the earth (in the adiabatic equivalent dipole field).

Another way of describing the particle contents, which is preferred by experimentalists, is by means of structure functions of the form

$$J_0(B, L, E) \quad \text{Eq. (8)}$$

where J_0 is the differential omnidirectional intensity of a given component on a magnetic shell specified by McIlwain's L value¹² and at a point whose scalar magnetic field value is B . Therefore, the integral omnidirectional intensity is

$$J_0(B, L) = \int_{E_0}^{\infty} f(E, B, L) dE \quad \text{Eq. (9)}$$

The following intensities and spectra have been given by the Working Group on Fields and Particles, during the recent summer study on space sciences at the State University of Iowa.¹³

Absolute Intensities

In Heart of Inner Zone ($L \sim 1.4$, $B = 0.12$, altitude ≈ 3600 Km)

Protons ($E > 30$ MeV), $J_0 \sim 3 \times 10^4 / \text{cm}^2 \text{ sec}$

Electrons ($E > 600 \text{ KeV}$), $J_0 \sim 2 \times 10^6 / \text{cm}^2 \text{ sec}$

Electrons ($E > 40 \text{ KeV}$), $J_0 \sim 10^5 / \text{cm}^2 \text{ sec}$

In Heart of Outer Zone ($L \sim 3.5$)

Electrons ($E > 40 \text{ KeV}$), $J_0 \sim 10^7 / \text{cm}^2 \text{ sec}$

Electrons ($1.5 < E < 5 \text{ MeV}$), $J_0 \sim 10^4 / \text{cm}^2 \text{ sec}$

Protons ($0.1 < E < 5 \text{ MeV}$), $J_0 \sim 10^8 / \text{cm}^2 \text{ sec}$

Protons ($E > 1 \text{ MeV}$), $J_0 \sim 10^7 / \text{cm}^2 \text{ sec}$

Protons ($E > 75 \text{ MeV}$), $J_0 \sim 0.1 / \text{cm}^2 \text{ sec.}$

Spectra

Protons in lower edge of inner zone:

$$J(E) dE \sim E^{-1.8} dE,$$

for $75 < E < 700 \text{ MeV}.$

Protons in outer edge of inner zone:

$$J(E) dE \sim E^{-4.5} dE,$$

Electrons in lower portion of inner zone:

$$J(E) dE \sim e^{-E/160} dE,$$

for $E > 40 \text{ KeV}$

Electrons in heart of outer zone:

$$J(E) dE \sim E^{-1} dE$$

for $40 < E < 150 \text{ KeV}$

$$J(E) dE \sim E^{-5} dE$$

for $300 < E < 5,000 \text{ KeV}$

Protons in heart of outer zone:

$$J(E) dE \sim e^{-E/100} dE$$

for $100 < E < 5,000 \text{ KeV}$

The time variations of the particle intensities in the geomagnetic field can be given generally as the following factors¹²

- (1) unity for $L < 1.8$ for protons with $E > 20 \text{ MeV}$
- (2) ten for $1.8 < L < 2.2$ for electrons with $E > 40 \text{ KeV}$
- (3) ten for $2.2 < L < 15$ for electrons with $E > 40 \text{ KeV}$
- (4) one hundred for $2.2 < L < 15$ for electrons with $E > 1.5 \text{ MeV}$

1.14 Solar Cosmic Radiation

Although it is important to consider the overall radiation environment when determining shielding requirements, solar cosmic radiation presents the major radiation problem in space (neglecting long term orbiting missions within the Van Allen belts). Solar cosmic rays are energetic charged particles emitted by the sun during solar flare activity. Not all flares are associated with solar cosmic rays that reach the earth. The radiation is known to consist of protons, alpha particles, heavy nuclei, and electromagnetic radiation of energy up to about 500 KeV.

1.141 Solar Flares

A solar flare (sometimes referred to as a chromospheric flare) is a short-lived sudden increase in H_{α} intensity occurring in the neighborhood of a sunspot. Only on a few occasions have flares been observed in white light. After its beginning, a large flare rapidly expands over a few million to a billion square miles of the solar disk and flashes to peak intensity in about half an hour or less. It then slowly decays in intensity and completely disappears within a few minutes for small flares to about 8 hours for very large flares.

All flares are observed in the plage regions around sunspots, and rarely does a flare occur more than 100,000 km from a sunspot. The greatest frequency of occurrence is associated with magnetically complex spot groups of the β (bipolar groups) and γ (complex groups) types.

Small flares appear as simple bright circular patches with no filamentary structure, but intense flares appear to be irregular patterns of bright filaments of the order of 10^4 to 10^5 km in size. In addition to the bright Balmer lines of hydrogen and the line of ionized calcium, the flare produces emission lines of HeI, FeII, and other metallic elements.

Visual studies of the flare structure made by Warwick¹⁴ reveal the following general geometrical properties: (1) flares are relatively flat structures extending parallel to the solar surface; (2) the thickness of a flare is three to four times the thickness of the chromosphere with the uppermost portions penetrating into the corona; and (3) flares are essentially stationary in time. These characteristics clearly differentiate flares from surges or eruptive prominences which rise high in the corona with velocities of hundreds of kilometers per second. The vertical motion in the growth of a flare rarely exceeds 10 km/sec.

The area of the solar flare on the disk of the sun at maximum brightness is the basis used for classification of a flare. The area is expressed in millionths of the visible hemisphere or in square degrees (1 square degree = 48.5 millionths = 3.13×10^4 km²). Table 1¹⁵ is a tabulation of flare importance.

TABLE 1
FLARE CLASSIFICATION

Type	Importance	Area	
		Millionths	Sq. Degrees
Subflares	1-	< 100	< 2.06
Flares	1	100-250	2.06-5.15
Flares	2	250-600	5.15-12.4
Flares	3	600-1200	12.4-24.7
Flares	3+	> 1200	> 24.7

A flare of importance 1, having an area of 100-250 millionths is rated 1+ if its intensity in H_{α} at maximum brightness is greater than the normal value for a class 1 flare. Similarly, a flare (class 2) having an area within the range of 250-600 mill. is rated 1+ if its intensity is H_{α} is much less than the normal value and 2+ if it is much greater. Likewise, a sub-flare, whose area lies within the range 50-100 mill., may be elevated to a class 1 status if it is unusually bright. Initially, the plus was assigned only to class 3 flares which caused geophysical phenomena.

1.142 Electromagnetic Radiation

Although solar protons are the predominant radiation resulting from solar flares, X-rays are also present. As the X-rays are of fairly low energy, they are easily attenuated by the atmosphere and

are therefore very difficult to observe at balloon altitudes. Rocket flights made by Chubb¹⁶ have detected a rather high flux of X-rays of energies up to 20 KeV accompanying three class 2 + solar flares. The results obtained for two flares in 1959 are listed in Table 2.

TABLE 2
X-RAYS FROM CLASS 2 + FLARES

	Counts/cm ² /sec	Counts/cm ² /sec	Ergs/cm ² /sec	Ergs/cm ² /sec
Date	2-8 Å	8-20 Å	2-8 Å	8-20 Å
8-14-59	1.3×10^4	2.0×10^6	5.7×10^{-4}	1.8×10^{-2}
8-31-59	7×10^5	1×10^7	3×10^{-2}	9×10^{-1}

A recent solar flare X-ray burst on September 28, 1961 has been reported by Anderson and Winckler¹⁷. X-ray observations have also been reported by Winckler, May and Masley¹⁸, and other authors.

Peterson and Winckler¹⁹ have reported the observations of a short burst of high energy X-rays during a balloon flight at 10 gm/cm² atmospheric depth over Cuba (30° geomagnetic latitude). The burst began approximately half a minute before the reported visual observation of a class 2 flare and the beginning of an SID on March 20, 1958. The duration of the X-ray burst was about 18 seconds and was identified as a

flash of approximately 0.5 MeV X-rays. The observed flux was 7.6×10^{-5} erg/cm².sec.

The biological danger of short wavelength electromagnetic radiation from flares appears to be very small and can be neglected entirely from present shielding considerations.

1.143 Particulate Radiation

Although protons are the predominant particles during solar cosmic ray events, alpha particles and heavy nuclei are also present. It is believed that electrons are present but there are only three cases in evidence. During the November 1960 events it was inferred by Ney and Stein²⁰ from their emulsion data that electrons of rigidity > 0.7 Bv constituted less than 2% of the observed radiation. Electrons were also reported during the September 28, 1961 event²¹ and the September 3, 1960 event³.

The average percentage of alpha particles in the total integrated flux for solar cosmic ray events is unknown. However, over a short period of time during an event, the number of alpha particles may be nearly equal to or greater than the number of protons. As reported by Ney and Stein²⁰, eight to ten hours after the flare of November 15, 1960 the ratio of protons to alpha particles at an energy greater than about

300 MeV was about 1. The corpuscular beam during the November 12, 1960 event was rather rich in alpha content, the ratio of protons to alphas being 2 to 1.²⁰ According to Biswas,²² the ratio of protons to alphas during the September 3, 1960 event was 30.

Heavy nuclei have been observed during a number of events. The September 3, 1960 event and the series of events of November, 1960 were especially well monitored. Table 3 is a tabulation after Ney and Stein²⁰ of various measurements of heavy nuclei.

Table 3
Heavy Nuclei in Solar Cosmic Rays

Event	Rigidity Interval (Bv)	J_P/J_α (> R)	J_P/J_M (> R)	J_α/J_M^* (> R)	Reference
Sept 3, 1960	> .57		1250	} 42	22
Sept 3, 1960	.87-1.32	30			23
Nov 12, 1960	.57- .87	5.5 0.8	330 60	60 75	24
Nov 15, 1960 9 hrs after flare	.81-1.08(p & α) & 1.18-1.45(CNO)	1	100	100	20
Nov 15, 1960 42 hrs after flare	.80		120	} 75	25
Nov 15, 1960 38 hrs after flare	.80	1.6			20

* J_M denotes flux of C, N, O Nuclei

Also during the November 12, 1960 event, it was reported that solar tritium was present at a ratio to protons of about 0.4% ²⁶.

The majority of solar cosmic ray protons are of low energy, the average energy for most events being 30-50 MeV. There have been 11 events since 1942 which included particles of high enough energy to be detected by sea level instruments. These events, often called "relativistic" (particles of energy in excess of 1 BeV are present), are very infrequent in their occurrence. Of these 11 events, six were of sufficiently high energy to be detected at sea level on a world wide basis, indicating the presence of particles of energy in excess of 15 BeV (the minimum energy allowed by the geomagnetic field at the equator). Table 4 is a tabulation of the dates of the 11 events (the 6 events mentioned above are noted by an asterisk).

Table 4

Dates of Relativistic Solar Cosmic Ray Events

* February 28, 1942	August 31, 1956
* March 7, 1942	July 16, 1959
* July 25, 1946	May 4, 1960
* November 19, 1949	* November 12, 15, 20, 1960
* February 23, 1956	

The average frequency for this type of event is about 4 1/2 years. Dodson-

Prince has noticed that these events seem to show a preference for occurring half way up or half way down the sunspot cycle. No relativistic event has been observed during the several month period around a sunspot maximum.

Although only 11 relativistic events have been observed since 1942, about 70 low energy events have been identified. Most of these events exhibit only small particle intensities and would have caused little if no biological effect. It should be pointed out however, that only a very few events have been observed well enough by different techniques to allow a reasonable calculation of free-space dose.

Because the proton energy range for low energy events extends from a few MeV up to about 500 MeV, observations must be carried out above the atmosphere to obtain enough data to completely analyze the event.

Relativistic events do not necessarily produce the largest biological problems. Noteworthy is the February 23, 1956 event, which included particles with energies exceeding 15 BeV. Using a spectrum similar to that of Winckler²⁷, Masley and Goedeke²⁸ obtained an integrated free space dose of only about 40-80 rad. It is also obvious, from the biological point of view, that the event of February 23, 1956 was not the largest one observed, rather, the May 10, 1959, July 14, 1959, and the November

12, 1960 events far exceed the February event in dose²⁸.

Protons contribute at least 90% to the integrated dose under 1 gm/cm² absorber for most events. Although the actual biological effects of protons are less than those for alphas and heavy nuclei (the RBE, relative biological effect, is higher for alphas and heavies), their number is so great compared to other particles present that they are the major concern to radiation shielding design. Fluxes have been observed to be as high as about 10^5 protons/cm²-sec of $E \gg 10$ MeV²⁹. It is thought that the highest flux for any event so far was about 6×10^7 protons/cm²-sec of $E \gg 30$ MeV (an extrapolated figure from data 31 hours after the July 14, 1959 flare)³⁰.

1.144 Frequency of Occurrence

The solar sunspot cycle referred to earlier is a variation in sunspot number having a period of about 11.3 years. Practically all of the sunspot activity occurs within two zones parallel to the solar equator and within $\pm 45^\circ$ latitude. The zones have an average width of $15^\circ - 20^\circ$ and rarely reach the equator. The first spots of a new cycle occur at about 30° N and S. At sunspot maximum the zones reach $\pm 15^\circ$ latitude, while the last spots of a cycle appear at about $\pm 8^\circ$. The migration of these zones in latitude follows a periodicity of about 11.1 ± 0.4 years which is more regular than the sunspot cycle¹⁵. Figure 1 is a plot of sunspot numbers between 1846 and 1959.

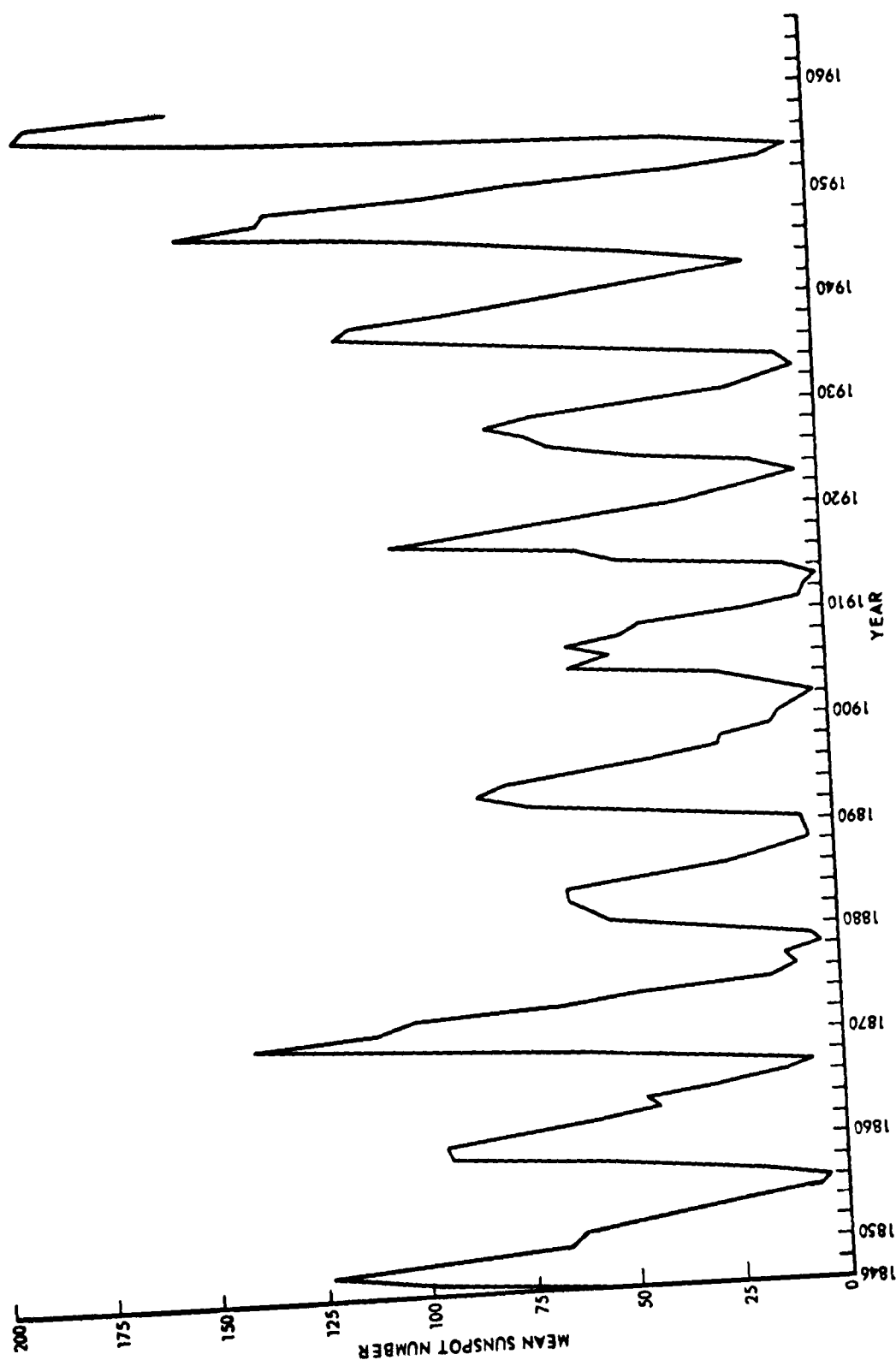


Figure 1 Mean Sunspot Numbers From
1846 Through 1959

The number of solar cosmic ray events follows closely the 11 year sunspot cycle. Figure 2 shows the relationship between the number of events and sunspot number. Although the maximum number of events is seen to occur at sunspot maximum, most of the major events occurred 1-2 years later. That this observation is meaningful is not known as only one cycle has been well observed. However, it is known that relativistic events occur more frequently on the descending side of the cycle and have never been observed near sunspot maximum. The reason for the apparent large number of events in 1960 is due to the series of 4 events in April, 3 in May, and 3 in November. The March 31, April 1, and April 5 events were associated with flares from the same region (McMath 5615). Also, the events of November 12, 15, and 20 were associated with the same McMath region. It may be prudent (from a frequency of occurrence point of view) to consider each series of events which evolved from the same active sunspot region as only one event. Using this criterion, the number of events in 1960 would be reduced from the plotted 12 to 8. Likewise, the number of plotted events for other years would be somewhat reduced although in many instances there is an uncertainty in selecting the flare which was associated with the radiation (2 or more flares occurred at approximately the same time in different locations).

The present solar cycle which began in 1954 and reached a maximum in

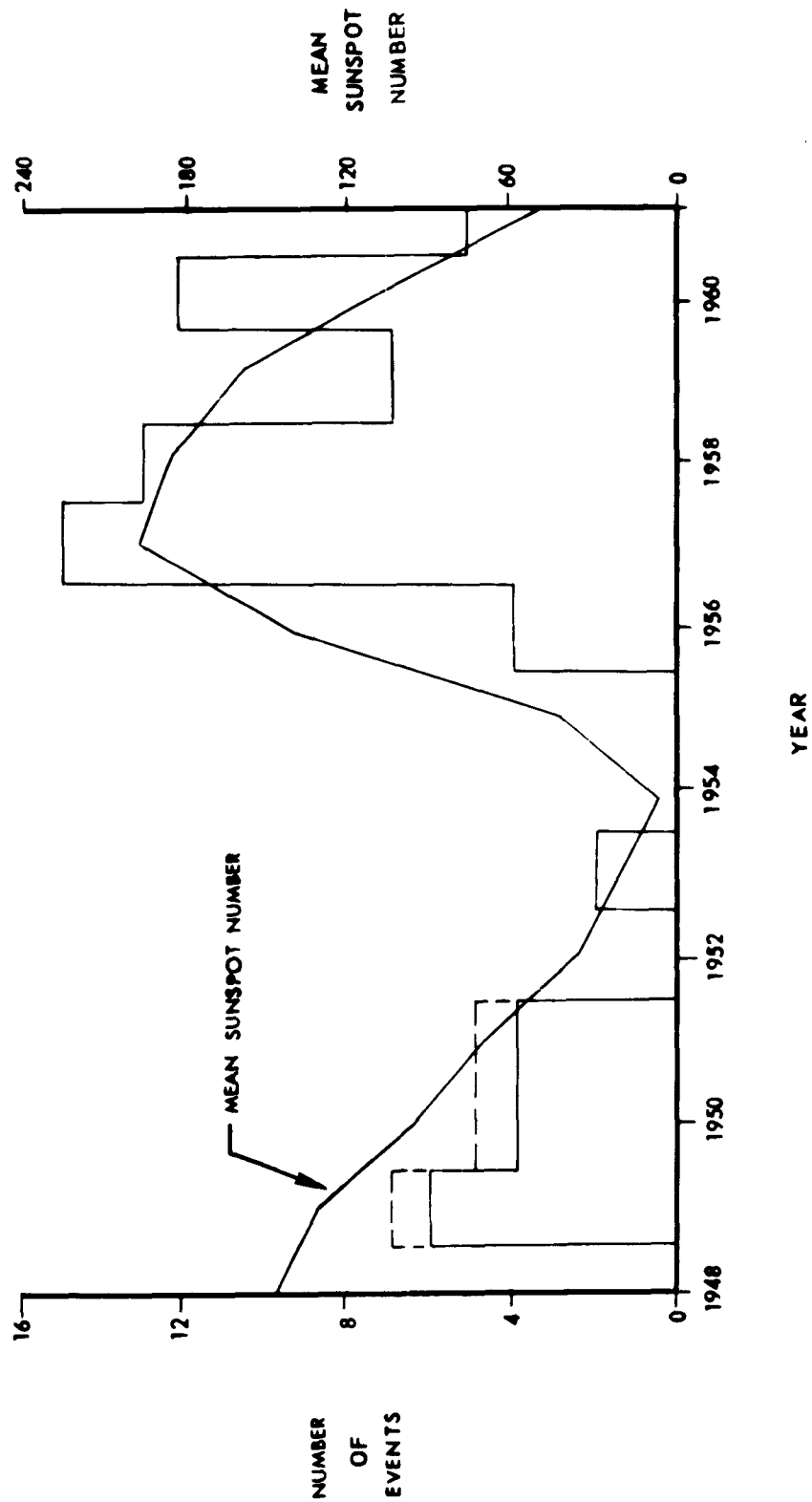


Figure 2. Relationship of the 11-Year
Cycle to the Occurrence of Solar Cosmic Ray
Events

early 1958, as expected to reach a minimum in 1965. This cycle resulted in more solar activity than any other observed cycle. It is expected that the next cycle which will peak in the 1968-1969 period will be considerably less active than the present ³¹.

Although the 11 year cycle is the predominate variation in the occurrence of solar cosmic ray events, there may exist other variations. As pointed out by Goedeke,³² Collins, Jelly, and Matthews,³³ Adamson and Davidson,⁴¹ and Warwick and Haurwitz,³⁷ there is evidence for an annual and perhaps semi-annual variation in the occurrence of polar cap ionospheric absorption events (solar cosmic ray events). From existing data and publications on ionospheric effects induced by solar cosmic rays, ^{32,33,34,35,36,37,38,40} from 1949 through 1961, a monthly distribution has been tabulated and plotted in Figure 3. From this it is clear that there has been a larger number of events during spring and summer months. 74% of all identified events between 1949 and 1961 have occurred during spring and summer. The minima in the monthly distribution are rather interesting, especially the December minimum (no events have ever been detected). Of the 5 events in June, 3 were so small that they are questionable. Table 5 is a tabulation of the dates of identified polar cap absorption events between January, 1949 and January, 1962. The events listed from January, 1949 through 1956 were identified by means of ionosonde data. All other events were identified by riometers (relative ionospheric opacity meter).

The most obvious explanation for the apparent seasonal effect is

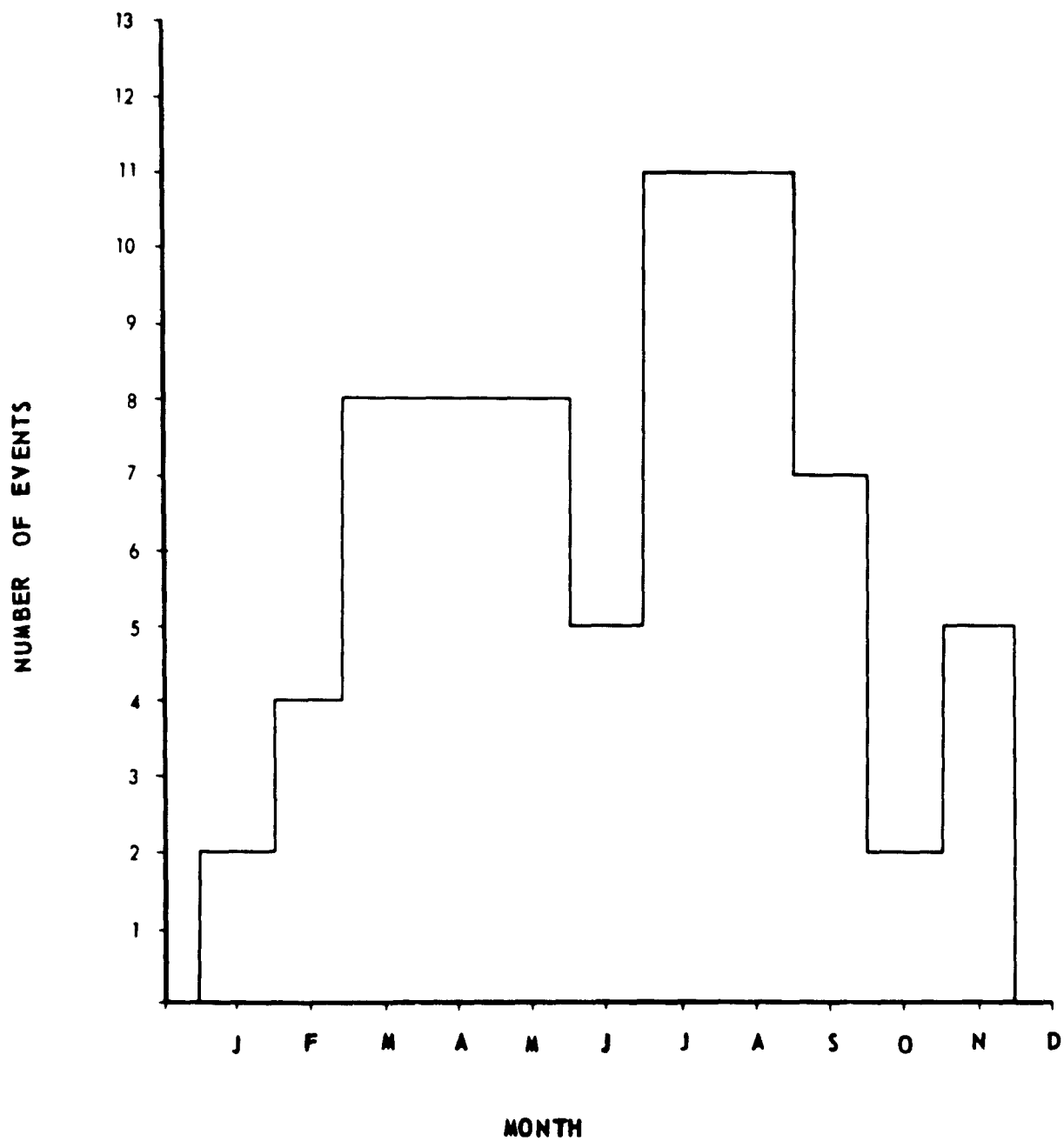


Figure 3. Monthly Distribution of Polar Cap Absorption Events for the Period of Jan. 1949 Through Jan. 1962.

Dates of Polar Cap Ionospheric Absorption Events

1961 - 1961

Date	Comment	Ref	Date	Comment	Ref	Date	Comment	Ref
1949			1955			1958		
Jan 23		33	No			Feb 10		35
Apr 11		33	Events		33	Mar 14		33
May 10		33				Mar 23	?	34
June 4		33				Mar 25	V. Weak	35
Aug 3		33	1956			Apr 10		35
Nov 19		33	Feb 23		33	Jun 6	V. Small	36
			Mar 11		33	Jul 7		35
1950			Aug 31		33	Jul 29		35
Feb 2		33	Nov 13		33	Aug 16		35
Feb 22		33	1957			Aug 21		35
Mar 27		33	Jan 20	Weak	33	Aug 22		35
May 27		33	Apr 3	Weak?	33	Aug 26		35
			May 19		35	Sep 22		35
1951			June 22	Small	35			
Mar 7		33	Jul 3		35	1959		
Apr 2		33	Jul 24		35	May 10		35
June 11		33	Aug 9		40	Jun 13	Weak?	39
Oct 27		33	Aug 29		35	Jul 10		35
						Jul 14		35
1952			Aug 31		34	Jul 16		35
No			Sep 2		35	Aug 2	V. Small	34
Events		33	Sep 12		35	Aug 18	Weak?	39
			Sep 21		35			
1953			Sep 26		35	1960		
Mar 2	V. Weak?	33	Oct 21		35	Mar 31	Weak	38
May 19	Small	34				Apr 1	Small	38
						Apr 5	Small	38
1954								
No								
Events		33						

that almost all observations have been from northern polar-cap regions. During PCA events, the nighttime absorption is very small compared to the daytime value, so that the possibility of detecting small ionospheric absorptions is greater during the long days of northern summer than during the dark winter months. The question then arises as to the differences between absorption measured by two identical instruments located in northern and southern polar regions. It is now known that there is little difference for large PCA events. Data will soon be available from the Douglas Geophysical Station at McMurdo Sound, Antarctica⁴², and the Douglas Conjugate Point Station at Shepherd Bay, NWT. Also, other riometer data from the Central Radio Propagation Lab of the National Bureau of Standards stations in Antarctica will assist in interpreting the differences in northern and southern polar-cap absorption.

The possibility of a semi-annual variation can be seen from Figure 3. Although there is some statistical significance in the December minimum, riometer observations through the next solar maximum are required to examine the reality of the June minimum.

Figure 4 shows the geometrical relationship between the earth's orbit and the plane of the solar equator. It is interesting to note that the apparent minima in Figure 3 corresponds closely with the June and December solstice (when the earth passes through the intersection of the plane of the solar equator and the plane of the ecliptic). However, it is doubtful if any possible connection between earth-sun geometry and the

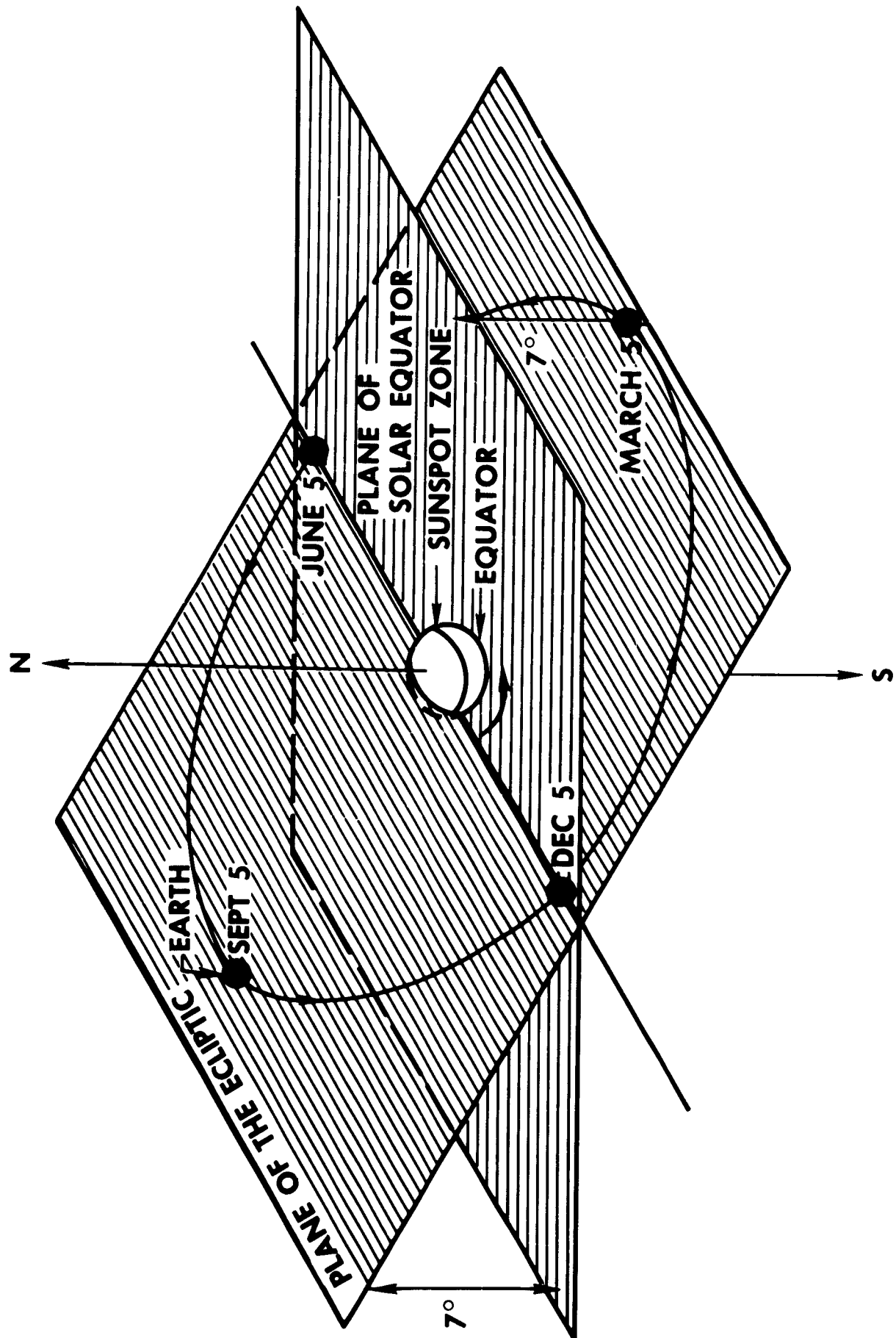


Figure 4. Geometrical Relationship Between the Earth's Orbit and the Plane of the Solar Equator

frequency of occurrence of PCA events can be established at present.

1.2 Space Radiation Doses

Although 71 events are listed in Table 5, there are enough data on only a few to allow reasonable dose estimates. The November 12, 1960 event was one of the most well observed to date. The analysis performed by Masley and Goedeke⁴³ resulted in perhaps one of the most accurate dose figures for any solar cosmic ray event on record.

It is doubtful if more than 20 events since 1949 resulted in a sufficiently high enough free-space dose to cause any extensive biological damage, and very doubtful if more than 5 events were near lethal (> 200 rad). Although the criterion used here is to define an "event" as an identifiable increase in particulate radiation associated with an identifiable flare, most of the large events included in the number 20 above occurred in a series (see Table 5). Considering a series of events (close to each other in time and which evolved from the same active region on the sun) to be one event, the number would be reduced from twenty. This method of counting events is perhaps more representative of the frequency of occurrence of solar cosmic ray events. When calculating probabilities of encountering solar cosmic rays during a space mission, account must be taken of the fact that many of the most intense events have occurred in a series of two or more. Also, calculations of the expected integrated dose for a

mission must be for a specific vehicle, for known shielding properties, and for a specific time during the sunspot cycle. The absorbed dose depends strongly on the geometry and type of shielding material and period of travel. Also, as present data on space radiation doses are scant, it is questionable that such probability calculations are even statistically significant.

With just a small amount of shielding (about 5 gm/cm^2 of Al), it is doubtful that more than 3 events since 1949 would have been lethal. Table 28
6 is a tabulation of integrated doses for solar, galactic, and Van Allen radiation. The range of calculated doses for solar cosmic ray events extends from about <1 rad to about 10^4 rad. Cosmic rays result in a dose of about 5 rad/year near solar maximum and about 10 rad/year near solar minimum. The dose would be larger if material shielding was present due to the multiplication of high energy particles.

There is still considerable doubt on the relative biological effect (RBE) of heavy nuclei. Until more data are available on RBE's for heavy nuclei as a function of various tissues and organs of the body, it will be prudent to give space radiation doses in rad ($\text{rad} \times \text{RBE} = \text{rem}$).

1.3 Biological Dose Restrictions

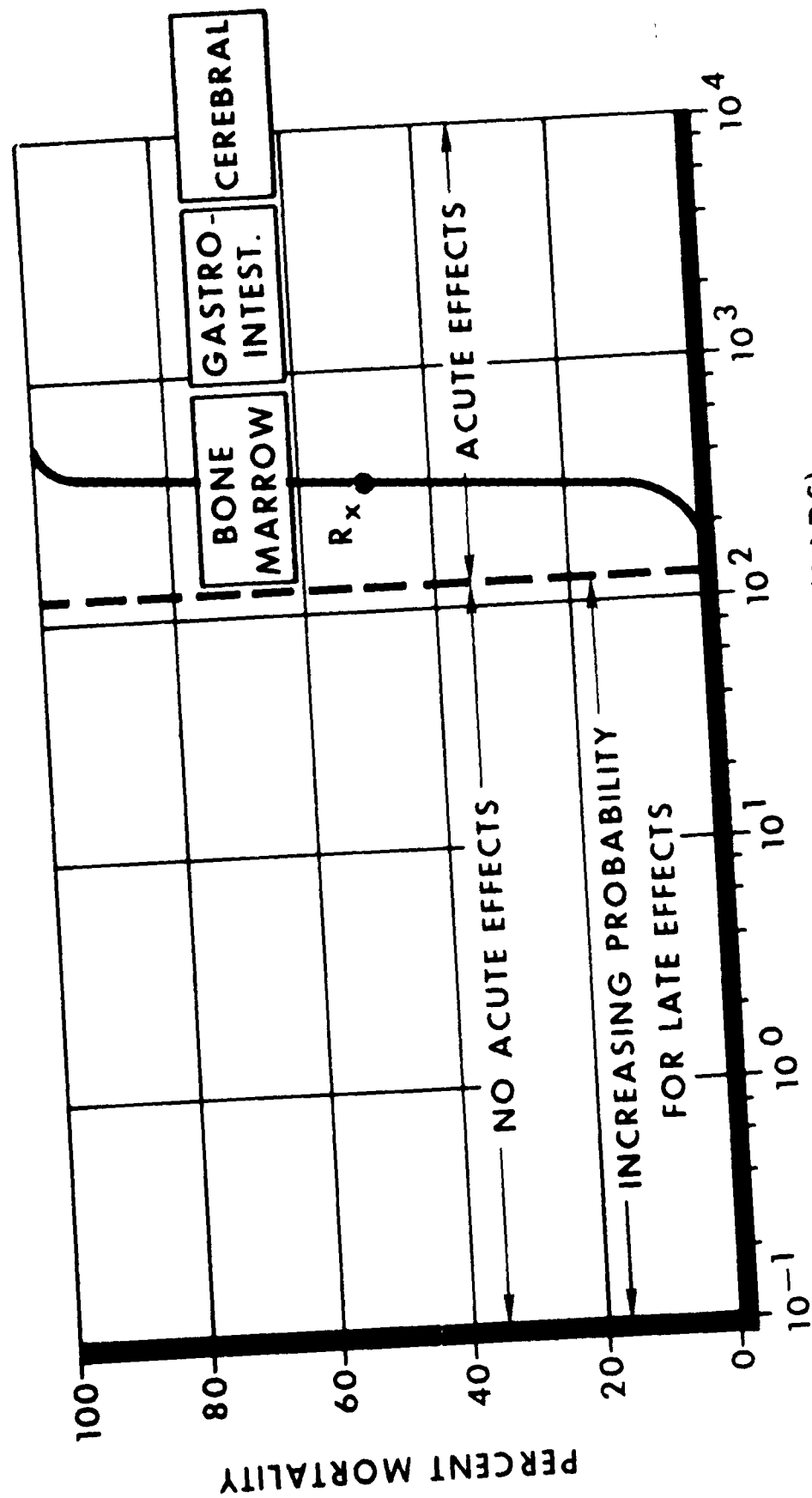
Figures 5 and 6⁴⁴ indicate the radiobiological effects upon humans from very energetic and low energy particle radiations. Since

Table 6. Integrated Space Radiation Doses
(Ref. 28)

44-7131A

EVENT	TYPE	AVERAGE ENERGY*	INTEGRATED DOSE*	COMMENTS
FEB. 23, 1956	CLASS 3 PLUS SOLAR FLARE	370 MEV	40-80 RAD	NO SPECTRUM INFORMATION BELOW 1 BEV AVAILABLE FIRST 19 HOURS
JULY 14, 1959	CLASS 3 PLUS SOLAR FLARE	46 MEV	3×10^4 RAD	3 EVENTS OCCURRED DURING SIX-DAY PERIOD TYPICAL FOR LARGE SOLAR COSMIC RAY EVENTS. (DOSE VALUE UPPER LIMIT OF TIME EXTRAPOLATION.)
MAY 12, 1959	CLASS 3 PLUS SOLAR FLARE	38 MEV	7×10^2 RAD	FIRST 11 HOURS EXTRAPOLATED FROM RIOMETER DATA.
APRIL 1, 1960	CLASS 3 PLUS SOLAR FLARE	40 MEV	1 RAD	WELL OBSERVED EVENT (PIONEER V, BALLOONS, SATELLITES, AND RIOMETERS).
NOV. 12, 1960	CLASS 3 PLUS SOLAR FLARE	50 MEV	1850 RAD	3 EVENTS DURING PERIOD; NOV. 12, 16, 20. NOV. 12 EVENT WELL OBSERVED. EMULSIONS DETECTED HEAVY PARTICLES.
JULY 18, 1961	CLASS 3 PLUS SOLAR FLARE	50 MEV	80 RAD	SIMULTANEOUS BALLOON OBSERVATIONS AT FT. CHURCHILL AND MINNEAPOLIS.
CONTINUOUS	GALACTIC COSMIC RAYS	4000 MEV	5 RAD (ONE YEAR)	INTENSITY VARIES BY FACTOR OF 2, INVERSELY RELATED TO SUNSPOT ACTIVITY.
PASSAGE THROUGH INNER VAN ALLEN BELT	TRAPPED RADIATION	144 MEV	6 RAD	1 HOUR PASSAGE.

* FOR GREATER THAN 30 MEV PROTONS UNDER
1 gm/cm² of Al



RADIATION DOSE (RADS)

Figure 5. The Biological Hazard of Penetrating Radiation (Ref. 44)

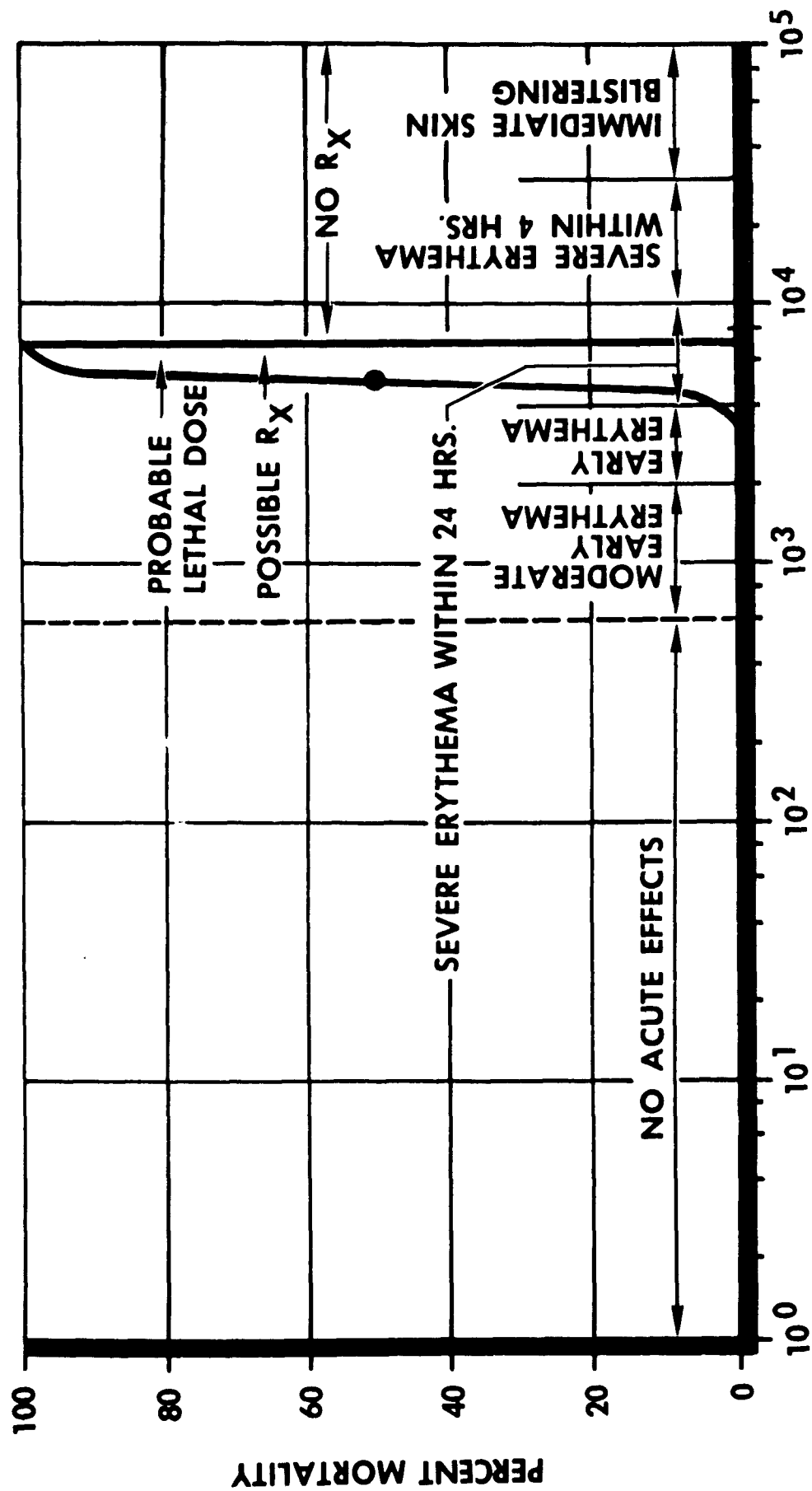


Figure 6. The Surface Hazard of Low Energy Radiation . (Reference 44)

solar flares consist of a heterogeneous beam of low and high energy particles two concepts must be considered. As may be seen from Figure 5 penetrating radiation doses up to 125 rads should on the average not result in any disease symptoms to man. The skin probably will absorb several thousands of rads (Figure 6) before it would acutely affect astronauts. In general, it can be assumed that depending on proton energy distributions, severe incapacitation from the penetrating radiations would occur before similar effects of the surface hazards would be noticeable. The latter would then at best only compound the former. It is known that the dose absorbed by the bone marrow, the site for blood cell production, will probably be the limiting factor in terms of disease and lethality. The main concern is then the ionizing radiation absorbed by this organ, followed in order of increasing liability to damage by the gastro-intestinal cells, the gonads, the germinal epithelium of the skin and finally, at doses of several thousand rads of penetrating radiations, the central nervous system.

According to Baum,⁴⁴ disease symptoms will become apparent at penetrating dose levels of approximately 125 rads, will increase in severity with increasing exposure and probably fatality (5% level) will commence at an absorption of approximately 250 rads. However, it must be emphasized that this does not mean that injury is not received below a dose

of 125 rads. As a matter of fact, a decrease in white blood cells can be measured after an exposure of 25 rads. Furthermore, animal experiments have demonstrated that exposures up to 100 rads will definitely result in late symptoms, such as tumors, cancers and a general decrease in life span. One may reasonably conclude that up to a dose of 125 rads no overt symptoms will make their appearance which could incapacitate astronauts.

1.4 Comparison of Dose Restrictions to Space Radiation Doses

According to Baum, fatalities will begin to occur at an absorbed dose of about 250 rad. As discussed above, it is doubtful if more than 5 events since 1949 have resulted in a dose exceeding 200 rad. The possibility is therefore small for encountering a lethal event during a short term mission (say to the moon) and very small during solar minimum. For long term missions (i.e., one year or more) which take place on the down-leg part of a solar cycle, the probability of encounter appears to be greater.

The majority of the observed events to date fall in the dose category of "no resulting acute effects". However, it is surmised that late effects will result, and that the seriousness of the effects will increase with increasing integrated dose. It will be important then on long term missions to make every possible allowance to minimize the integrated dose. Because the probability of encountering a large event

increases with mission duration, it will be prudent to utilize radiation protection of some form.

In general, the dose level of most solar cosmic ray events is less than that required to cause any serious long or short term biological effects. Because the dose varies by many orders of magnitude for solar cosmic ray events, and because the time variations and other properties are usually different for each event, it is not possible to construct an "average event" or even determine the average dose over the identified events.

The long term effects to be expected from exposure to energetic heavy nuclei in galactic cosmic radiation are still uncertain. However, there is some evidence that the heavy cosmic ray particles do not pose a serious biological problem.⁴⁵

1.5 Shielding

Before a detailed radiation shielding system can be designed for a particular mission, acceptable biological dose rates and integrated doses must be established. Moreover, the anticipated integrated dose must be established. For example, it is important to consider whether the integrated effect is made up of 100 rad doses from many events or 10^4 rads from one event.

As mentioned earlier, protons constitute the major radiation problem in space. The need for shielding has been established and since we are mainly concerned with charged particles, there are two basic shielding methods, namely, "active" and "passive".

1.5.1 Active Shielding

Deflection of incoming particles can be accomplished by the use of electromagnetic or electrostatic fields. Felten⁴⁶ has examined several simple electrostatic shielding configurations as to charge stability and ability to reduce the biological dose. It was found that some of these configurations are catastrophically unstable against discharge, and that all of them subject their occupants to unacceptable doses of bremsstrahlung X-rays due to collection of solar photoelectrons and plasma electrons by the high positive potential.

Felten has concluded that such systems are not feasible under interplanetary conditions, although with new advances in engineering and space vehicles, there may be some merit in certain complex electrostatic configurations.

To create a magnetic field of such magnitude as to deflect high-energy charged particles would require an enormous amount of power. Levy⁴⁷ has investigated electromagnetic schemes and concluded that magnetic fields

may be advantageous for only charged particles of energies of the order of 1 BeV because of the weight involved. The use of superconductivity may be the key to realistic electromagnetic shielding in space. However, it does not appear prudent to consider magnetic fields for short term missions or for any mission within the next few years. Long term missions would certainly result in a low integrated dose if magnetic fields could be employed. However, the present state of vehicle payload capability makes such a shielding method doubtful. With the advent of nuclear powered vehicles, large payload weights will become practical and adequate shielding can be made available.

1.5.2 Passive Shielding.

Passive shielding is the use of inert material or a composite of materials to attenuate and absorb radiation. Because of their large stopping powers for charged particles and their low yields for production of secondary radiation, low atomic number materials such as hydrogen, hydrogeneous compounds, carbon, etc. are superior shielding materials. However, aluminum, beryllium and magnesium are almost as effective as hydrogeneous materials and have the advantages of structural properties. Although secondary radiation production is higher for high Z materials*, it has been found⁴⁸ that the amount of dose from secondary particles at depths greater than a few gm/cm^2 only adds a few percent to the dose from the attenuated protons. This is a negligible consideration in view of the fact that the

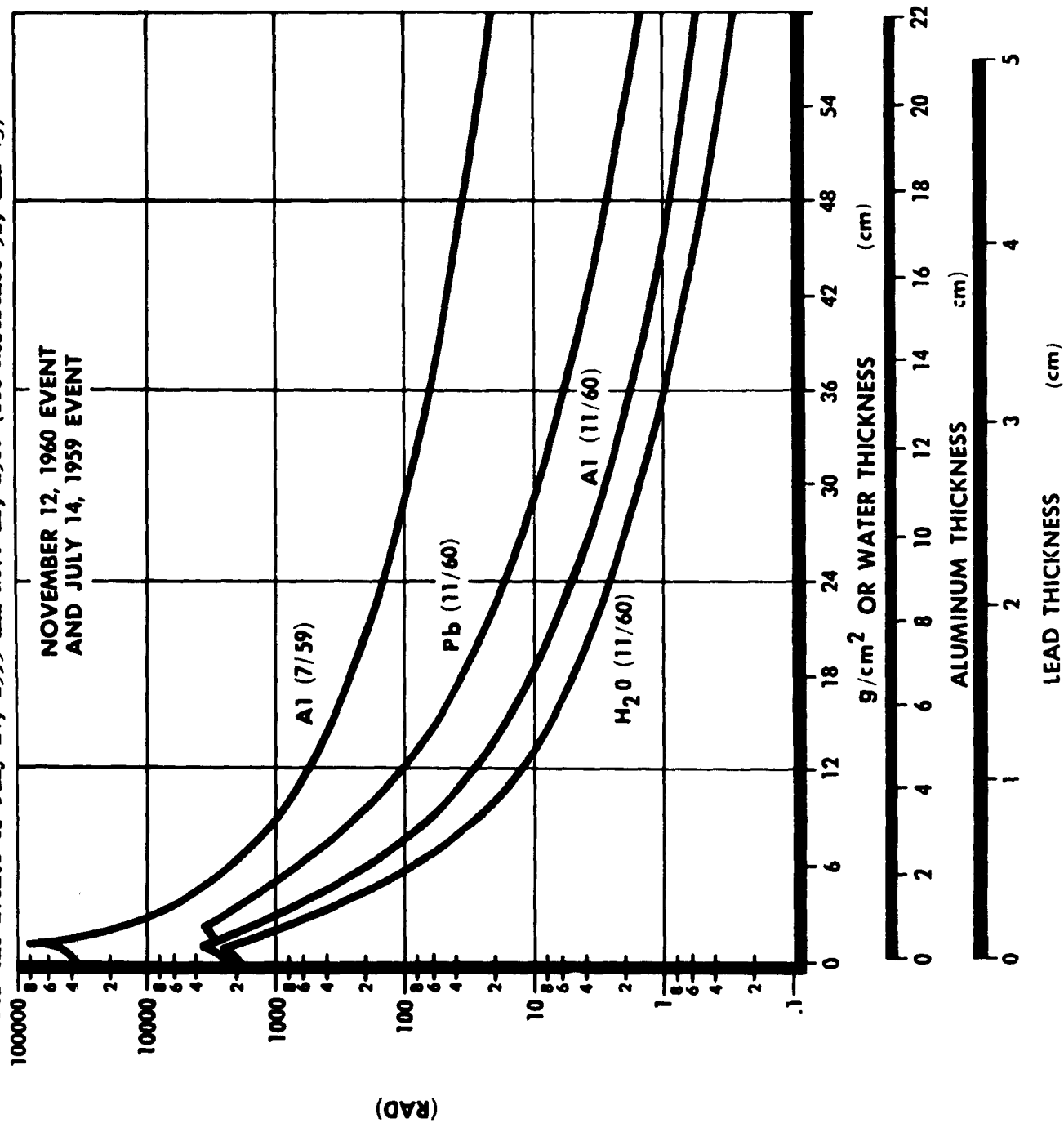
* Z-Atomic Number.

integrated doses are not known to high accuracy at the present time.

Other authors have also found this to be true.⁴⁹

A comprehensive study of material shielding and secondary production has been carried out by Wilson, Miller, and Kloster.⁵⁰ Their conclusions are that secondary radiation is a very important factor in any shielding calculation. However, they find this to be true at depths exceeding about 20 gm/cm^2 of medium Z materials. Figure 7 shows the dose as a function of depth in Al, Pb, and H_2O for the November 12, 1960 event⁴³, and in Al for the July 14, 1959 event.⁵¹ It can be seen that at depths of 20 gm/cm^2 or greater in Al, the primary proton dose for the November 1960 event is already less than 10 rad and less than 300 rad for the July 1959 event. These two events gave the largest known doses ever observed but there is some doubt about the measured particle fluxes during the first 30 hours of the July event. The dose of 3×10^4 rad should probably be considered an upper limit. It thus appears that on short term missions it is unnecessary to consider the secondary particle dose at depths greater than about 20 gm/cm^2 during solar cosmic ray events. On long term missions, where the integrated dose is of concern, secondary particle doses may be important, especially from galactic cosmic rays and relativistic events.

Figure 7. Dose as a Function of Shielding Depth
For the Events of July 14, 1959 and Nov. 12, 1960 (see Reference 51, and 43)



1.6 Prediction of Solar Activity

Long term prediction of the general level of solar activity can be made with some accuracy. Records of sunspot observations over many years have established the 11 year periodicity in the sunspot number. That the number of solar cosmic ray events per year is somewhat proportional to sunspot number is shown in Figure 2 . This criterion provides at least a first order approximation of the level of solar activity. The present cycle (number 19) resulted in the largest sunspot numbers ever observed. There is thought to be a cyclic variation in peak sunspot number with a period of 170-180 years. Due to uncertainty, even if this periodicity exists, the peak of the next cycle (1969) cannot be forecast either as the high point in the long variation or as the beginning of a new long-term variation with a low maximum sunspot number. Utilizing the two or three year period during the minimum of a sunspot cycle to conduct manned space missions is presently the most reliable technique to reduce the solar flare hazard.

Short-term prediction techniques of any assured accuracy do not exist. Methods have been proposed which depend on continuous solar observations. One method proposed by Anderson⁵² depends on optical measurements of penumbral area around active sunspots. Another method proposed by Weddell⁵³ depends on the measurement of indices of individual active regions. The indices are the area and intensity of plages seen in the K_3 line of CaII, the

duration of 200 Mc/s radio emission, and the structure of the longitudinal magnetic field in the photosphere below the plage region. The need for accurate short-term prediction is obviously great if manned space missions are to be carried out during periods of maximum solar activity.

Another method proposed by Goedeke³² relies on the observed monthly distribution of polar cap absorption events from January 1949 to January 1962. A criterion which is proposed is to use the months of June and especially December for short term manned missions. This criterion, together with observational techniques may provide some radiation safety for near future missions such as Apollo.

1.7 Conclusion

It has been shown that the space radiation environment poses a definite problem to manned space flight. Only the biological problems have been discussed, although radiation problems with materials, electronics, and secondary power systems also exist. Of primary concern are solar cosmic ray events which, as of now, cannot be predicted in advance with high reliability. Although enough criteria may exist to predict in advance with some reliability the occurrence of a large solar flare, the dose and/or flux of the radiation cannot be predicted.

This is easily seen to be true by comparing the July 18, 1961 and the July 14, 1959 events. The originating flare for both events was a class 3+ flare. It looked about the same for both cases, although the difference in free-space dose was probably 3 orders of magnitude. However, when flares can be accurately predicted in advance, a criteria will exist which will enable delay of a space mission or a warning so that man will be able to have time to abort a mission or seek shelter if available.

The frequency of occurrence of polar cap absorption events requires increased investigation through the next solar maximum. Of special importance are simultaneous riometer measurements at magnetic conjugate points in the polar regions. Recent theory indicates that multi-frequency riometer measurements can provide energy spectra during large solar cosmic ray events. The use of new multi-frequency riometers will be advantageous in providing additional data for analyses of PCA events. As the next few years will be a period of minimum solar activity, it is expected that few if any large solar cosmic ray events will occur. It is important however, that continuous observations be made through the period of sunspot minimum so that any events that may occur will not be missed. During 1962, the Douglas geophysical station in the antarctic registered a number of absorption events, all very small. These events are presently being analyzed.

Until more information is available on biological effects of space radiation, space doses in rem, and prediction techniques, it will be prudent, if shielding cannot be utilized due to weight problems, to utilize the period of low solar activity and perhaps the months of December and January as probable safe periods for short term missions.

Acknowledgements

The author wishes to thank K. A. Anderson and A. J. Masley for their helpful comments and suggestions, and M. B. Baker and T. Henderson for shielding data.

Addendum

On page 5, paragraph 3, it is stated that the energy range of galactic cosmic rays extend from tens of MeV up to at least 10^{12} MeV. A recent publication (J. Liasley, Phys. Rev. Letters, Vol. 10, p. 146, 1963) indicates that the upper limit can be increased to 10^{14} MeV.

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