Lawrence Berkeley National Laboratory
Recent Work

Title

PARTICULATE RADIATION: ELECTRONS, PROTONS UP TO CARBON

Permalink

https://escholarship.org/uc/item/626429t7

Authors

Tobias, Cornelius A.
Wallace, Roger.

Publication Date

1960-10-26

eScholarship.org
Powered by the California Digital Library
University of California

UCRL -9446

UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence

Radiation Laboratory

TWO-WEEK LOAN COPY

This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545

BERKELEY, CALIFORNIA

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

PARTICULATE RADIATION: ELECTRONS, PROTONS UP TO CARBON

Cornelius A. Tobias and Roger Wallace
October 26, 1960

PARTICULATE RADIATION:
ELECTRONS, PROTONS UP TO CARBON

Cornelius A. Tobias and Roger Wallace

Lawrence Radiation Laboratory
University of California
Berkeley, California

October 26, 1960

ABSTRACT

The properties of galactic and solar cosmic rays are discussed and compared. Their composition, energy distribution, intensity, time variation and low-energy cutoff by the earth's magnetic field are described. The demography of the cosmic-ray energy in the atmosphere is treated. Cosmic rays produced by solar flares, their implications to space travelers, and the shielding needed to protect the travelers from these rays are described. Dose rates measured by using spare probes and balloons are compared. Data for a carbon shield are given. For design purposes, dose rates appropriate to space travel are included.

PARTICULATE RADIATION: ELECTRONS, PROTONS UP TO CARBON

Cornelius A. Tobias and Roger Wallace

INTRODUCTION

The nature of primary cosmic rays will be discussed with only those constituents from electrons and protons up to carbon being described in detail. Consideration will be limited for the most part to cosmic rays as they exist at distances of several earth radii and further in the local solar system. The secondary radiation produced by these cosmic rays when they impinge on the atmosphere will be briefly dealt with and the effect of the geomagnetic field on the incident particles and the effect which this has on radiation at various radii will be described. The shielding which cosmic rays make necessary for any interplanetary vehicle carrying living organisms will be briefly described.

Origin

Although the origin of cosmic rays is still somewhat in doubt, the general characteristics which they exhibit when they reach the earth can now be described in some detail. They have been studied for many years. It has recently become apparent that there are two main categories present. The first category consists of those cosmic rays which originate outside of the solar system. We will call them galactic cosmic rays. Whether they originate in the galaxy or outside of it is not completely settled at this time. The second category will be those which originate in the sun. These are called solar cosmic rays, or solar flare cosmic rays. We will limit our discussion to particulate radiation, and will not consider electromagnetic radiation, such as photons, x-rays, or gamma rays which might be present in space.

Galactic Cosmic Rays.

The galactic cosmic rays approach the earth in what appears to be an isotropic spatial distribution. Their intensity varies by about a factor of 2 with an eleven year period. This is interpreted as being the result of magnetic activity arising in the sun in connection with its eleven year sunspot cycle. The original galactic cosmic rays are therefore presumed to be relatively constant in time. This constancy in time appears to go back in history at least a half million years, and probably much longer.

The constituents of the galactic cosmic rays are largely the same as the constituents of the known univers, as is seen in Table I.(1) In this table some more recent data from Winkler(2) has been added to the original data of Harrison Brown. It is seen that the relative abundances of primary cosmic rays from the galaxy are not exactly the same as the presumed relative abundances of the elements in the universe, however the differences are well within the generous experimental errors. The nuclear species present in cosmic rays can be directly measured and therefore this part of the data is probably more accurate than the relative abundances which are more difficult to measure since much of the matter in the universe is obscured. At any rate, although it is not important to our present purpose, it appears that galactic cosmic rays are an average sample of the universe which has been accelerated to very high velocities. A similar comparison of composition can be made to that of early stars, or the composition of planetary nebulae. When this is done, it is also found that the distribution of elements in the primary cosmic rays from the galaxy is not too different from the distribution in these other sources.

A comparison of the distribution of elements in the sun's atmosphere, and in the galactic cosmic rays, shows some very great differences. This finding shows that only certain types of cosmic radiation originate in the sun. The background radiation of steady cosmic rays appears to originate in the more distant parts of our galaxy, rather than in the sun.

A very fortunate situation exists in the case of cosmic rays, in that we are provided by nature with a spectroscopic analyzer in the form of the earth's magnetic field. This magnetic field makes it impossible for particles below certain energies to reach the top of the atmosphere at certain latitudes. Many investigations have been made in the last few years, with balloons, rockets, and, at high mountain altitudes, with emulsions and various types of electronic detectors. These investigations have made it possible to unfold the original spectrum of primary cosmic rays, both in energy and in mass. From this data the following facts emerge. The integral spectrum for proton energies can be expressed by

$$N_p\,(>E) = \frac{0.3}{(1 + E)^{1.5}} \quad \text{particles/cm}^2\ \text{sec sterad;} \qquad (1)$$

$$500 < E_p < 2 \times 10^4,$$

Where E is in Mev, and the average energy is 4 × 10^3 Mev per nucleon. This energy distribution does not represent the very top of the spectrum where there are particles with as much energy as 10^{18} electron volts.

Particles other than protons exhibit similar energy distributions, as shown by Singer$^{(3)}$ in Table II, and plotted in Figure 1. It is seen that the exponent of the total energy (1 + E) in the various integral energy distributions is roughly constant for most of the different atomic species in the galactic cosmic rays. This similarity of spectrum offers some difficulty and provides some suggestions for explaining the original acceleration of the cosmic rays; it tends to favor those theories in which the cosmic rays are accelerated in large bundles of plasma, or in shock waves, rather than in the same manner as particles in a synchrotron or cyclotron. These latter types of acceleration would separate out the various values of e/m. The lower energy limit of the galactic cosmic ray spectrum seems to be about 100 Mev. Whether this is a real lower limit or whether it is the result of a screening of the earth from the original source by some magnetic field or absorption process is not known. At any rate lower energy cosmic rays are apparently absent in the vicinity of the earth.

As an upper limit, one can take 1% for the proportion of electrons in the primary cosmic rays. This of course does not infer a lack of electric neutrality, since there can be a current of electrons toward the earth to compensate for the flux of positive primary cosmic ray particles, so that the earth as a whole maintains charge neutrality. The energy carried by these balancing electrons is quite small. Also less than 0.1% of the initial energy flux above the atmosphere is due to x or gamma rays.

Puppi(4) gives the energy which is delivered to the earth by primary galactic cosmic rays as shown in Table III and IV. In free space in the vicinity of the earth during times of minimum sunspot activity the energy flux is about 1,400 Mev/cm^2 sec steradian. It is interesting to note that when the cosmic rays strike the atmosphere, and are degraded by a variety of processes, that this 1,400 Mev/cm^2 sec steradian is not all accounted for when a breakdown is made of the eventual fate of the various forms of energy in the atmosphere. For example, as seen in Tables III and IV, the energy balance can be made in two different ways. First by the various ways that it is dissipated in the production of charged or neutral pions and nuclei. This total is 965 Mev/cm^2 sec steradian. The energy can also be broken down in its ultimate destination as either being dissipated in ionization, neutrinos, or used to overcome nuclear binding forces. Of course some energy eventually hits the earth. The total, so broken down, is also 965. However slightly more than 400 Mev/cm^2 sec steradian are not accounted for by this process.

The figures in Tables III and IV are quoted for times of minimum solar activity and therefore maximum galactic cosmic ray intensity. The eleven year solar sunspot cycle decreases the incident galactic cosmic ray intensity as the number of sunspots increases. During a period of solar maximum the values are approximately one half of those quoted. At such a period of solar maximum, which has just recently passed, it is found that the energy density of galactic cosmic rays in the vicinity of the earth is about 0.6 ev/cm^3. This corresponds to 8700 Mev/cm^2 sec from a 4π solid angle in outer space, or 700 Mev/cm^2 sec steradian. An ionization chamber calibrated with radium gamma rays will give about 0.6 mr/hr inside of a one gram/cm^2 absorber, or about 5000 mr/yr in outer space at a period of maximum sunspot activity.

In addition to this eleven year cycle, there are much shorter Forbush decreases which are observed to be associated with solar flares and solar magnetic disturbances. These decreases are interpreted as being the result of magnetic fields thrown off by the sun deflecting the galactic cosmic rays away from the earth. These decreases amount to as much as 25 or 30 percent and last for a few days.

Figure 2 shows the ionization that is received at various geomagnetic latitudes at 10 grams/cm^2 depth in the atmosphere, at solar minimum, solar maximum, and during a Forbush type brief decrease. It is seen that the cosmic ray galactic background rate which is shown here varies by a factor of about two between solar minimum and solar maximum, of course inversely as the number of sunspots. This effect is not seen at the low latitudes, because the magnetic field, which produces either the Forbush type decrease or the change between solar minimum and solar maximum, is not strong enough to eliminate the most energetic particles, those above 15 Bev, which can penetrate to the top of the equatorial atmosphere. These decreases should be expected to exist throughout the local solar system and are not just a phenomena related to the earth's particular position or magnetic field.

Solar Cosmic Rays

Since 1942 there have been five events in which large increases in the sea level counting rate of neutron monitors, situated at many locations, around the world have been observed. These monitors give a response which measures the flux of incident neutral particles at the earth's surface, which is related to the flux of incident charged particles at the top of the atmosphere. Since there are essentially no incident neutrons or other neutral particles in the original cosmic rays, the flux measured by these instruments, called Simpson piles, consists entirely of secondary particles produced in the air by the incident charged primaries. It is now known that these sudden large increases in cosmic ray counting rate are directly associated with solar flares. A flare is a jet of very high energy gas which is shot out by the sun, and can be observed visually. In every known case the increase in cosmic rays as measured in the vicinity of the earth has been associated with an observed solar flare on our side of the sun.

A great deal has been written about solar flares since they apparently represent our main radiation problem in interplanetary space. In a typical flare the cosmic ray counting rate begins to rise within about one hour after the visible flare is sighted. The rise in counting rate is quite steep, reaching its maximum in a few minutes or hours. After the peak value is reached, the intensity of the cosmic rays will drop off gradually with time. The energy spectrum of the particles shot out by the sun has been inferred from the latitude effect on the increased counting rate of detectors, using the earth's magnetic field as a spectrometer. It is found that the energy spectrum of these particles of solar origin is considerably steeper than that observed in the case of the primary galactic cosmic rays.

In Figure 3 is seen the integral rigidity spectrum for the giant flare of February 23, 1956, at various times after the onset. At the bottom of the figure the primary proton spectrum which exists at times of solar minimum is shown for comparison and it is seen that the flare increased the proton flux by four or five orders of magnitude at relatively lower energies and that the flare spectrum is considerably steeper than that of the galactic background represented by the solar minimum curve. Also included for comparison is the spectrum of particles from an event of May 12, 1959. Even though the February 1956 flare has received a great deal of attention and has become the classic example of a giant flare it is interesting to see that the May 12, 1959 event actually had more low energy particles. We receive about one of these giant flares every four years and any long term space flight must take them into consideration. Also from Figure 3 it is seen that it is important to know the spectrum of such an event since shielding against five Mev protons is quite trivial, while shielding against 400 Mev protons and their neutron secondaries may be very expensive or prohibitive in weight. A small shift in the spectrum causes an enormous change in the shielding that is necessary around any space vehicle intended for occupancy by higher animals. It would seem to be very difficult under any circumstances to shield out the prompt flux from the February 1956 flare. It is not too difficult to provide sufficient material to use up the range of the protons, but the secondary neutrons formed in such a shield present a problem of great seriousness.

In the case of the February 1956 flare the cosmic ray intensity at sea level increased by as much as a factor of twenty in some northern latitudes. Even at the equator, where the minimum primary cosmic energy that can effect the counting rate at sea level is 15 Bev per proton, due to the magnetic field of the earth, there was an observable rise, meaning that the spectrum of the flare particles extended to at least 15 Bev. The particles of one Bev energy above the atmosphere increased by a factor of 1000 and particles of a half Bev energy increased to fluxes of 10^4 to 10^5 particles/cm^2 sec for many hours. It is estimated that an airplane flying at 50,000 feet in northern latitudes would have received a dose of 5 to 10 rads, if it was aloft during the entire flare. For practical purposes this would mean only the first few hours. It should be noted in this connection that only the charged particle flux is being considered, and that the dose due to neutrons produced in the atmosphere in this particular situation might easily equal or exceed that due to charged particles.

A distinction can be made between large solar flares that produce a measurable change in the cosmic ray flux on the surface of the earth and nonrelativistic flares which can only be detected at high altitudes or outside of the atmosphere. This distinction is probably an artificial one, and merely represents a historical separation of the early work which was limited to flares detectable at the surface of the earth from those which are now easily detected by satelites, space probes and balloons. These nonrelativistic flares are probably the low energy part of a continuous distribution which includes the giant flares in its upper energy tail.

There have been five large events in the past eighteen years, on February 28 and March 7 in 1942; July 25, 1946; November 19, 1949; and February 23, 1956. Of these the largest and the most famous is the event of February 23, 1956. At the peak of this giant solar flare the flux in outer space may have been as high as 10,000 particles/cm^2 sec. In this flare the flux of particles with energies greater than one Bev may have been as high as 1000/cm^2 sec. Probably all the particles were protons. After about an hour the intensity began to decrease following a relation such as that given by

$$\frac{I}{I} = \left(\frac{t_0}{t}\right)^2 = \left(\frac{t_0}{t}\right)^{3/2} = e^{-0.6\ t} \qquad (2)$$

at one hour later tens of hours later

where I_o and t_o are the intensity and time, at about one hour after the onset of the flare.

Some flares have been known to last for hours or days indicating that there is a storage mechanism involved whereby the particles can be retained in a structure which might be called a magnetic bottle which swings around with the sun. The visible flare usually does not last this long. Some flare particles have been observed to swing behind the sun and return for a second time after a full solar revolution. The solar cosmic ray particles apparently are always contained in a 2π solid angle or less located at the site of the optically visible flare on the surface of the sun. An estimate indicates that a few percent of the total energy contained in such a solar flare is actually put into charged particles which are emitted into space, some of them striking the earth. The integral energy spectrum of such a flare can be represented by

$$N(>E) = \frac{C}{E^6} \qquad (3)$$

Since only a few giant flares are observed and only one of these has occurred during the time when recent observational techniques have been available such as space probes, quick balloon ascents and local earth satelites, most of our experience with flares has been derived from the more frequently occurring nonrelativistic flares.

The nonrelativistic flares are limited to particles whose energies are approximately in the range from 40 Mev to 500 Mev. They may achieve an intensity as much as a factor of a million above the quiescent background in outer space. About one such flare and accompaning cosmic ray increase is occurring per month, during the present epoch of maximum solar sunspot activity. Comparable experience is not available with other periods of solar cycle since our observational methods were not highly developed before 1957. The flares occur in regions on the sun which have a complex sunspot pattern and in every case of increased counting rates near the earth a visible optical offshoot has been observed on the near side of the sun. There is some correlation between the area on the sun where the visible flare occurs and the time delay before the resulting cosmic rays strike upper atmosphere.

Generally speaking this time delay is about one hour for a class two or class three flare. At the same time as the flare, type IV radio noise is observed. As a result of the magnetic field of the earth and the relatively low energy of the particles emitted by a nonrelativistic flare, the particles are observed in the upper atmosphere only within about twenty or thirty degrees of the north magnetic pole. The integral energy spectrum of such a flare is given by:

$$N(>E) = \frac{C}{E^5} \quad \text{or} \quad \frac{C}{E^4} \tag{4}$$

The differential energy spectrum for the complete integrated energy distribution above the atmosphere for a representative nonrelativistic flare can be approximated by:

$$N(E)dE = \frac{24 \times 10^{12} dE}{E^4} \text{ protons/cm}^2 \text{ sec steradian} \tag{5}$$

Where E is in Mev and the distribution is normalized to the entire outburst. The particular flare described in Eq. 5 would have given an integrated dose inside of a one gram/cm^2 absorber of about 60 rep.

A nonrelativistic flare is usually first detected near the magnetic pole, about thirty minutes after the optical event. The flare then spreads to lower latitudes and after a few hours begins to decay. The decay follows the $1/t^2$ relation of Eq. 2. Many hours or days may elapse before the increased intensity has gone back to the galactic background level. If a magnetic storm accompanies a relativistic flare, the particles may be observed as far south as 40° from the magnetic pole. Due to the lower energy of flare dosmic rays this is only possible when the earth's magnetic field is distorted by such a storm.

It is now possible to say that particles observed near the earth from balloons and rockets and satelites appear to be the same as those measured at considerable distances from the earth. For example, the Pioneer V space probe made some very nice measurements when it was 5,000,000 kilometers from the earth. This data was found to be coincident in time with local measurements made near the earth's surface. In general, there is a magnetic storm one or two days after the onset of a visible flare which has nonrelativistic cosmic ray particles accompanying it. Measured intensities during such flares have varied from a few particles/cm^2 sec to as many as $10^6/cm^2$ sec. A few representative flares are listed in Table V. Dose rates as high as a few thousand r/hr have been noted, even in the case of nonrelativistic flares. As a result of the $1/t^2$ time dependence, the main dose is given by a flare during its first hour.

Based on the simultaneous experience gained through the measurements of Pioneer V and local balloons, factors are now known by which balloon dose rate measurements can be multiplied in order to give dose rate values which will be observed in free space. The particle flux and dose rate measured by a balloon must be multiplied respectively by factors of 65 to 82 to give the particle flux and dose rate expected in free space. It is seen that in the case of each of the flares listed at the top of Table V and also in the case of the background galactic cosmic rays that particle fluxes of a few thousand particles/cm^2 sec correspond to 1 rep/hr. The only exception to this case is the 23rd of Feb event where the flux is 200 (protons or particle /cm^2 sec)/(rep/hr).

In this brief review of the various types of radiation met with in space, there should of course be some passing remark about the Van Allen radiation belts. These very famous regions have received a great deal of attention. It is clear that they will present a serious problem in the operation of a satelite at altitudes contained inside the belts. However, for a space traveler who merely wishes to pass through the altitudes encompassed by the belts the radiation problem is not particularly serious. According to Schaefer$^{(5)}$, the passage through the Van Allen belts, in about 1 hour, even in nothing but a space pressure suit (0.2 grams/cm^2) will give the astronaut about 5 r each way. Hence the radiation belts are not such a serious problem for travelers to Mars as they are to occupants of satelites orbiting below 25,000 kilometers. The dose of 5 r which would be received in passing through the two Van Allen belts is certainly not worth the trouble of avoiding the belts, especially when it is realized that more than a space suit would always be available for protection from the Van Allen belt radiation. Any ordinary vehicle would probably provide fairly good protection for passing through the Van Allen belts. Schaefer shows that in the case of two different possible types of orbits traversing the Van Allen belts that the integrated dose accumulated in the inner belt would amount to about 1 or 2 r. This would increase to about 3 to 5 r while passing through the outer belt. In view of this very modest dose it would seem to be unnecessary to pursue the question of Van Allen radiation belts further at this time.

Radiation Dose from Cosmic Rays from Protons to Carbon

In Figure 4 is seen a plot which shows dose rates in mrep/24 hrs at various altitudes above the earth measured in earth radii as a function of the geomagnetic latitude. It is seen that the geomagnetic effect is largely wiped out at distances of three or four earth radii and from that point out that the galactic cosmic ray background amounts to about 26 mrep/24 hours or 9.5 rep per year. If an RBE >1 is used this number would be somewhat increased.

In view of the very high energy of the primary cosmic rays it would be difficult to reduce this very much. Due to the buildup factor in fact any practical shield would probably only increase the dose. Since the 10 or more rep per year received from the galactic cosmic rays is sufficiently small so that men could recover from it continuously and show no gross impairment of activity over a period of a few years, it is perhaps more pertinent to closely examine the problems which arise in connection with the large solar flares.

For example we may take a flare which occurred on the 10th of May 1959, which has been considered in detail by Robey.(6) This was a typical class 3+ flare. There were about ten flares of this size in 1959. This was a reasonably active year and near the top of the solar cycle. The flare of July 14, 1959 was larger, and both of these flares were considerably smaller than the famous flare of February 23, 1956. To an unshielded man in space near the earth the doses would probably have been lethal. The flare was located at 19° north and 50° west on the sun. The optical beginning was at 2102 UT May 10, 1959. The continuum type IV radio emission began at 2116 UT and lasted for 4.3 hours. The type II radio noise began at 2122 UT, while the cosmic noise absorption measured at College Park, Alaska began at 0100 UT on May 11, it was greater than 17 decibels and lasted for more than 30 hours. There was a Forbush decrease of 15%, recorded at 0400 on May 12. This Forbush decrease began at 0030 UT on May 12. The flux at the peak of the flare was not known, but a balloon flight was launched twenty nine hours after the beginning and this recorded 100 particles/cm^2 sec steradian, with rigidities greater than a half Bev. This measurement was made at a pressure altitude of 10 grams/cm^2, or about 100,000 feet. The differential kinetic energy spectrum was

$$N(E)dE = KE^{-4.8}\,dE \qquad 110 \text{ Mev} < E < 220 \text{ Mev}. \tag{6}$$

and the integral rigidity spectrum was

$$N(>R) = 0.75/R^{6.8} \text{ protons/cm}^2 \text{ sec steradian} \tag{7}$$

where R is expressed in Bev. There is no quantitative data for that part of the spectrum below 110 Bev. However, it will be assumed, for the purposes of this calculation, that the distribution given in Eq. 6 holds down to 23 Mev. This assumption is based on the experience gained with other flares by Van Allen, Rothwell, and others at Iowa State.

The integral of Eq. 6 from 23 Mev up to infinity gives 3×10^4 protons/cm^2 sec steradian. If we had started the integration at 30 Mev the answer would have been 1.3×10^4 protons/cm^2 sec steradian, so the difference is not very great. If the spectrum is cut off at the top end at about 400 Mev, which is twice the measured maximum particle energy, then the total integrated flux would be 0.75 protons/cm^2 sec steradian. The flux of approximately one proton/cm^2 sec steradian is assumed to exist at about one astronomical unit from the sun for several hours following the flare in the region above the Van Allen trapped particle zones around the earth. This flux is taken to be omni-directional. It is assumed that the average energy loss by the flare particles in striking an object is about 6 Mev/gram of target which is a value that is probably reasonable in view of the energy spectrum. Then for one proton/cm^2 sec steradian the dose will be 47 rep/hr. An unshielded cubic centimeter of tissue would, using an RBE of 2, receive 94 rem.

At the time of the flux measurements, 30 hours after onset, this flare was found to be decaying exponentially, with a time constant of 0.58/hour. The accumulated dose from 30 hours to infinity would therefore be 160 rem. Then assuming that the dose rate of 47 rep /hr was constant for the thirty hours before the flux was measured, and then decayed as $E^{-0.58t}$

we get $30 \times 47 + 80 \cong 1500$ rep. If, on the other hand, it is assumed that the flare started at a much higher level than the measured 30 hour level, which is certainly reasonable, and the decay was by the same exponential law--which is somewhat different from the experience gained in previous flares--then the total dose to an unshielded man from this flare would have been much greater than 1500 rep.

Making a rough calculation about the shielding, we will assume that carbon is used as a shield. Carbon is attractive from several points of view. It is relatively inexpensive, a very poor source of secondary neutrons, reasonably light in weight, and a good neutron moderator. The important point to remember is that a low Z material that does not easily emit neutrons is desirable. The radiation dose from neutrons plus protons for a spherical carbon shield, of varying thickness from 0 to 20 centimeters, is shown in Figure 5. It is seen that the dose can be brought down by a 20 centimeter carbon shield to fairly acceptable values of about 15 r. If such a flare occurs once a month, there is a very serious question whether 15 r is sufficiently low. To reduce the dose much further very extensive shielding is necessary, since the secondary neutrons with their very long attenuation lengths are the controlling factor after the shield reaches about 20 centimeters in thickness. The mass of such a shield with a 90 centimeter inside radius would be 14,000 pounds, and the net dose would be 14 rem, 6 rem from protons and 8 rem from neutrons. It is seen that, even from such a modest flare, the shielding requirements are quite severe and only one cramped crew member could be protected.

A Large Flare

Early rough calculations based on the classical flare of February 1956 indicated that inside of 1 gram/cm^2 of shielding the dose integrated over the entire flare would be about 600,000 rads. If one used a shield of carbon 180 centimeters thick in all directions, the dose inside from such a flare due to charged particles would be about 10 rads. There would be an additional dose due to secondary neutrons produced in the shield of about 30 rads. If one uses an RBE of 10 this is a very dismal situation. More recently Winckler(2) has estimated the maximum dose rate from this flare as 50-60 r/hr in space. Thus a dose for the whole flare of about 600 is more likely. This would make the shielding more like that described in Figure 5. It is fortunate that flares apparently have rise times measured in minutes, thus allowing the crew to move into a shielded cabin area after the onset of the flare before they receive any significant radiation dose.

Thus the radiation problem associated with solar flares is apparently the most serious question about the ultimate possibility of men flying to the moon or near members of the solar system. If one takes a pessimistic viewpoint, then one would estimate that approximately once a month, during periods of solar maximum activity, doses of several tens of rads might be encountered,

To provide shielding in such a situation might involve too much of a weight penalty. This probelm is sufficiently critical so that intensive study of solar flare activity will be necessary. Most of our knowledge stems from a period of solar sunspot maximum and it would be very interesting to see with what frequency the so called nonrelativistic flares occur in periods of minimum solar activity. It is known that the very largest flares which can be detected at sea level can occur even in periods of minimum solar activity.

If nonrelativistic flares also occur with approximately their presently observed frequency then the radiation problem is going to present severe limitations. If dose attenuations of 10 to 1000 are required, as seems to be indicated by several flares that have been observed so far, the shielding requirements will certainly be severe. It is conceivable of course that a space vehicle could be designed in such a way that the biological shielding could be provided by material which also has other functions such as the fuel reserve intended for the final retardation upon nearing the earth after the return trip. Other alleviations of the problem might be achieved, such as continuous treatment for radiation sickness and other prophylactic measures.

One of the most important questions to be answered aside from acquiring more data on the size distribution of solar flares occurring during various periods of the solar cycle is the biological question of just what maximum dose rates can be tolerated relative to the possible benefits of interplanetary or lunar flight. In the case of interplanetary flights, times of more than a year are usually indicated, and frequently as much as three years will be necessary. Therefore we must think seriously of the accumulated radiation dose which we can tolerate over such a period and still maintain the efficiency of the crew. It is claimed that a dose rate of 10 rem/day for a year will cause a few deaths, while a dose rate of 3 rem/day over a similar period will probably cause no deaths, and no noticeable drop in operating efficiency. If this is true, it would mean that approximately 1000 rem/yr can be tolerated, in which case the problem perhaps can be solved by a combination of a short trip, some shielding, prophylactic measures with regard to radiation sickness, and traveling at a period of minimum solar activity.

It certainly is clear, however, that any attempt to stay within the present pro rata occupational five rems per year over a period of many years or even 12 rems/yr, the present maximum occupational dose rate, is completely out of the question. It would appear to be quite unrealistic to try to limit crew members to the present occupational exposure level which has been selected to produce no observable biological effects over a lifetime of work, when at the same time we allow test pilots to lose twelve years of their life expectancy merely by their occupation. On the other hand it would seem to be important not to allow more than approximately 50 rems in a short period of time, in order to avoid difficulties with radiation sickness, which set in at levels above 100 rem. To exceed 100 rem in a few days would seriously impair the efficiency of the crew.

It has been suggested by several that solar flare radiation is perhaps radially directed from the sun and that a shadow or umbrella shield would be possible. This seems to be unreasonable, in view of the long storage times known to be associated with this type of radiation, which would tend to indicate that the flare protons are more or less isotropic, and that the earth should be considered to be enveloped in a large cone extending from the sun. Within this cone the radiation approaches from all directions. Also it is impractical to try to avoid flare radiation by advance warning methods. Even though it is true that the optical onset of the flare can be observed before the radiation arrives, and longer prediction based on the character of the associated sun spot patterns has met with some success, the lead time secured is so short as to not leave time for evasive action on long missions.

Table I

Abundance in Universe Due to H. Brown(1)

Z	Element	Atoms/10^5 H		Relative Abundance in Cosmic Rays	
1	Hydrogen	100,000		100,000	
2	Helium	7,700		15,500	
3-5	Li Be B	~ 0.1		240	
6	Carbon	23		260	
7	Nitrogen	46	~200	?	~1200
8	Oxygen	63		260	
10	Neon	2.6 - 70		30	
12	Magnesium	2.5		40	
14	Silicon	2.9		30	
26	Iron	5		30	
	$Z \geq 10$	30		400	
	$Z \leq 30$ not listed	2.7		100	
	$30 < Z \leq 92$	~0.1		<10	
				117,900	

Table II

Z	Range of validity E_t = Gev/nucleon	Integral spectrum in particles/cm^2 sec steradian	Limits of Exponent
1	$2 < E_t < 20$	$0.4 \; E_t^{-1.15}$	1.05 - 1.25
2	$1.5 < E_t < 8$	$0.046 \; E_t^{-1.6}$	1.3 - 1.7
3, 4, 5		~50% of CNOF flux	
6, 7, 8, 9	$3 < E_t < 8$	$0.0024 \; E_t^{-1.6}$	1.45 - 1.75
>10	$3 < E_t < 8$	$0.0016 \; E_t^{-2.0}$	1.85 - 2.25

Table III

Energy Expended in Particle Production by Cosmic Rays in the Atmosphere

Energy dissipated through production of charged pions	409	Mev/cm^2 sec sterad
Energy dissipated through production of neutral pions	256	"
Energy dissipated by the nucleonic component	300	"
Total	965	"

Table IV

Ultimate Destination for Cosmic Ray Energy in the Atmosphere and Earth

Energy which goes in ionization	615	Mev/cm^2 sec sterad
Energy which goes in neutrinos	232	"
Energy set against the binding of nuclei	80	"
Residual energy at sea level	38	"
Total	965	"

TABLE V (Revised)

Examples of Galactic and Solar Cosmic Rays as Measured with Balloons and Space Probe

Type of Experiment	Date	Time UT	Particle Flux	Dosage Rate	Type of Radiation	Particles/cm^2 sec / r/hr
Free Space (Pioneer V)	11-23 March 1960	-	4.6/cm^2 sec	0.0006 r/hr	Protons, α-particles, etc. 10^8 - 10^{17} ev	7670
Free Space (Pioneer V)	1 April	1200	33/cm^2 sec	0.026 r/hr excess	Protons 40 - 500 Mev	1270
Balloon	1 April	1200	0.4/cm^2 sec	0.0004 r/hr excess	Protons 90 - 500 Mev	1000
Balloon	-	-	2/cm^2 sec	0.0004 r/hr	Galactic C.R.	5000
Balloon	15 July 1959	1100	215/cm^2 sec	0.140 r/hr	Protons 90 - 500 Mev	1540
Ratio $\frac{\text{Pioneer V}}{\text{Balloon}}$	1 April	1200	82 ×	65 ×	Protons	
Free Space (Inferred)	15 July	1100	1.76×10^4/cm^2 sec	9.1 r/hr	Protons 40 - 500 Mev	1940
Free Space (Inferred)	14 July	0600	1.5×10^7/cm^2 sec	7.6×10^3 r/hr	Protons 40 - 500 Mev	1970
Free Space (Inferred)	23 Feb 1956	-	10^5/cm^2 sec	50-60 r/hr		200

Figure 1.

The integral energy spectrum of primary cosmic rays is shown as a function of the kinetic energy per nucleon. The figure shows the primary spectrum separted into four constituents: nucleons as a whole, protons, helium, carbon, nitrogen, and oxygen, and $z \gtrsim 10$. The magnetic cutoffs for 30, 41, and 55 degrees magnetic latitude are shown. It should be noted that the cutoff at the equator for protons is 15 Bev.

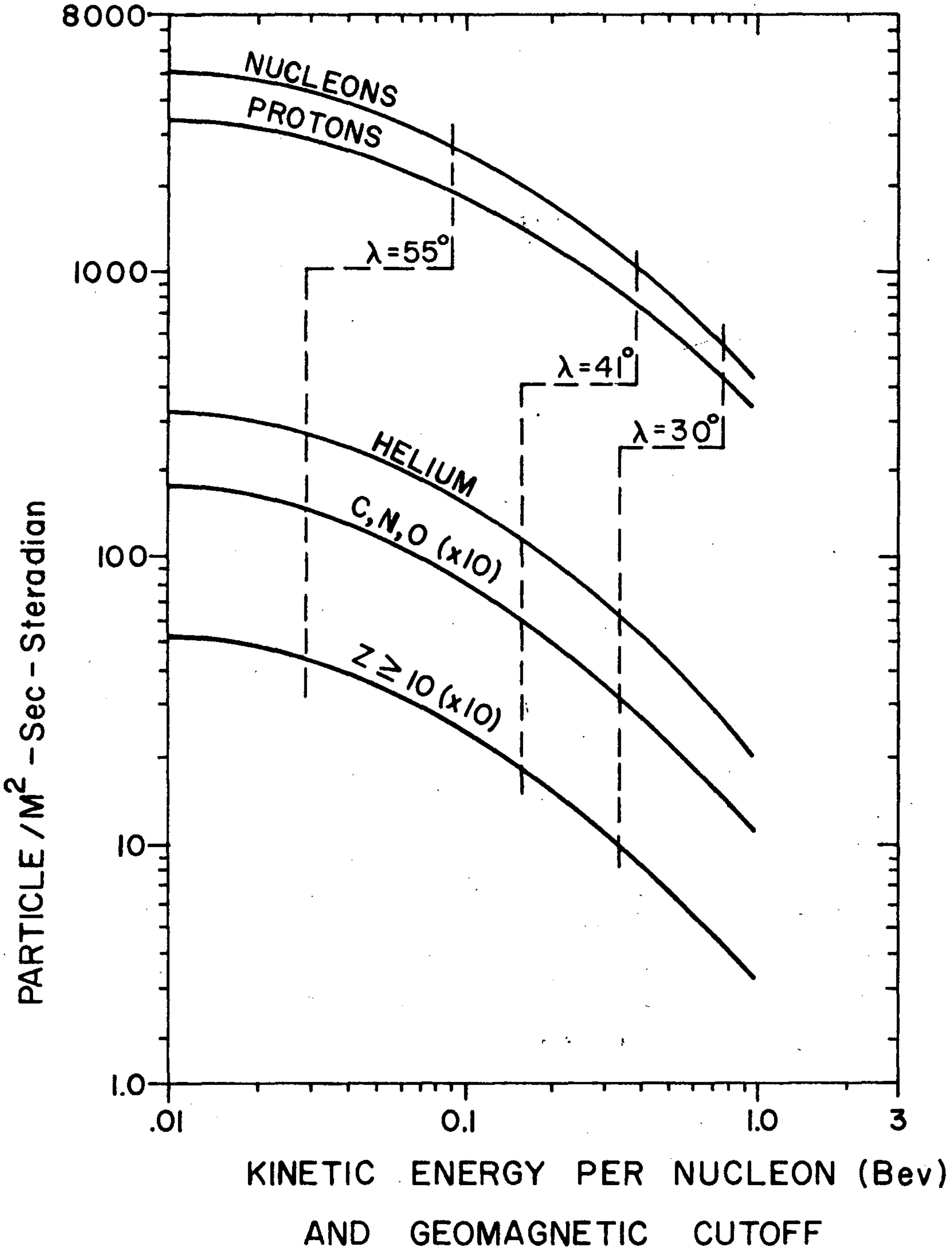
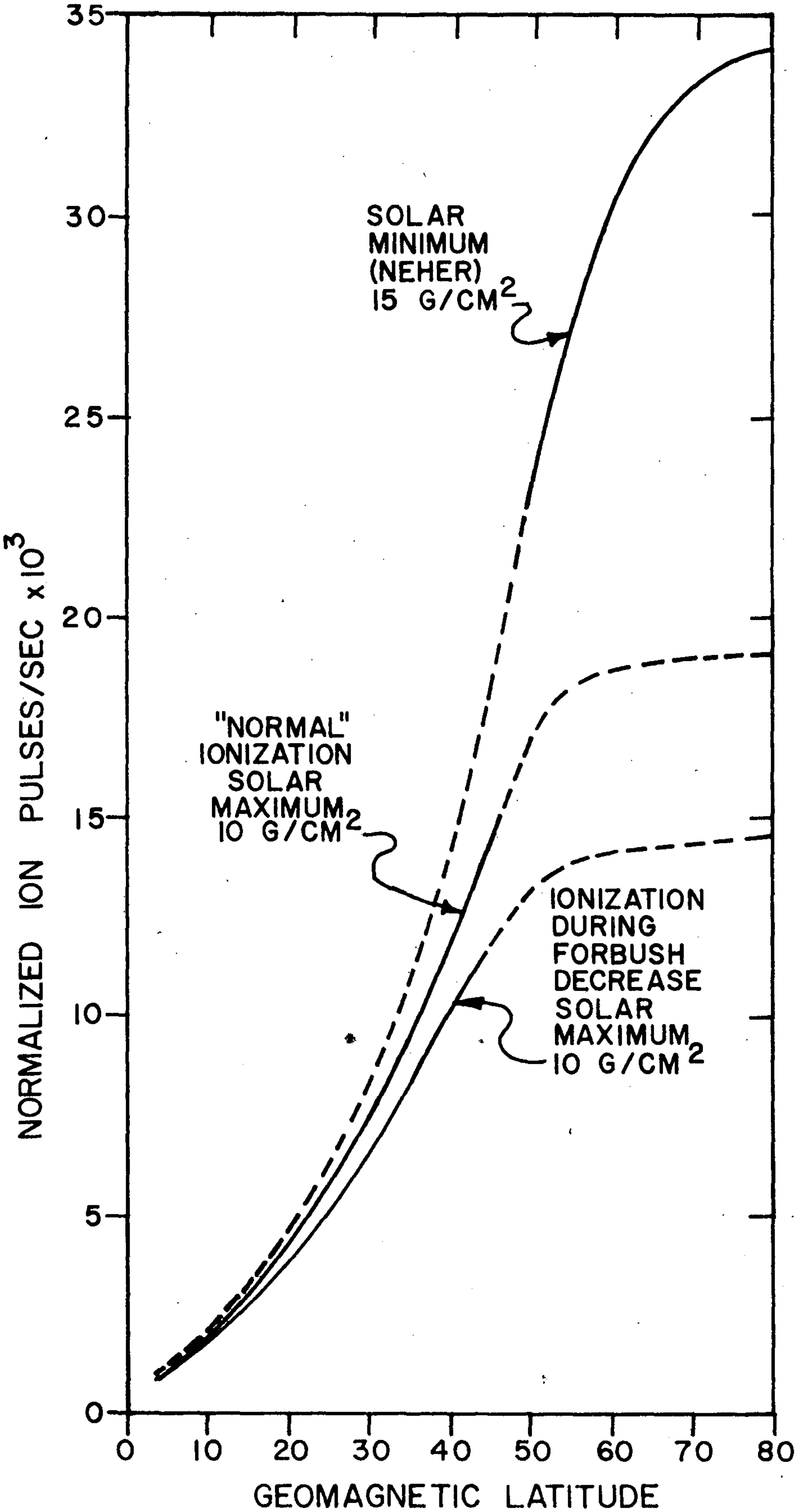

8000
1000
100
10
1.0
.01
0.1
1.0
3
PARTICLE / M² - Sec - Steradian
KINETIC ENERGY PER NUCLEON (Bev)
AND GEOMAGNETIC CUTOFF
NUCLEONS
PROTONS
λ=55°
λ=41°
λ=30°
HELIUM
C, N, O (x10)
Z ≥ 10 (x10)

Figure 2.

The ionization produced at a depth of 10 grams/cm^2 in the atmosphere as a function of the geomagnetic latitude for a period during sunspot maximum, minimum, and during a magnetic storm which produces a Forbush decrease. There is about a factor of two change with the sunspot cycle at latitudes above 50°.



35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
NORMALIZED ION PULSES/SEC x10^3
GEOMAGNETIC LATITUDE
SOLAR MINIMUM (NEHER) 15 G/CM^2
"NORMAL" IONIZATION SOLAR MAXIMUM$_2$ 10 G/CM^2
IONIZATION DURING FORBUSH DECREASE SOLAR MAXIMUM$_2$ 10 G/CM^2

Figure 3.

The integral magnetic rigidity spectrum for flare protons and quiescent primary cosmic rays. The variations with time in a single flare or between flares are very large and have a big effect on the dose. The flare spectra are steeper and several orders of magnitude above the background for energies less than about 400 Mev.

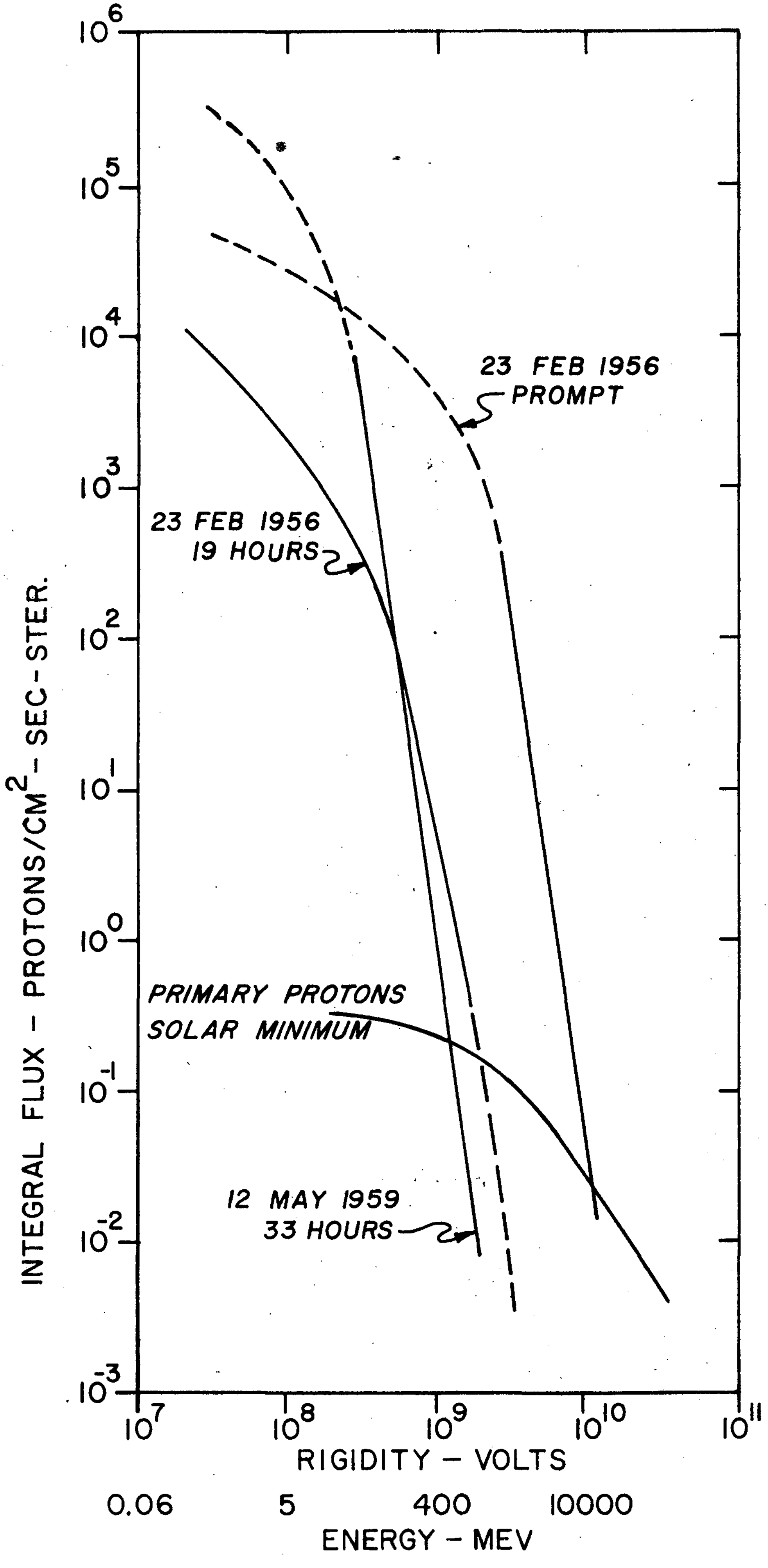

10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
INTEGRAL FLUX - PROTONS/CM^2 - SEC - STER.
23 FEB 1956
PROMPT
23 FEB 1956
19 HOURS
PRIMARY PROTONS
SOLAR MINIMUM
12 MAY 1959
33 HOURS
10^7
10^8
10^9
10^10
10^11
RIGIDITY - VOLTS
0.06
5
400
10000
ENERGY - MEV

Figure 4.

Dose rates in mrep/24 hours for charged cosmic rays and for secondary neutrons escaping from the atmosphere. The charged particle curves are from Nelson(7) and the neutron curves are from the methods outlined in Hess, et al.(9) and a private communication. Note that an RBE of ten has not been applied to this data and also that the neutron curves have been shifted up one cycle for compactness. The neutron dose is not important.

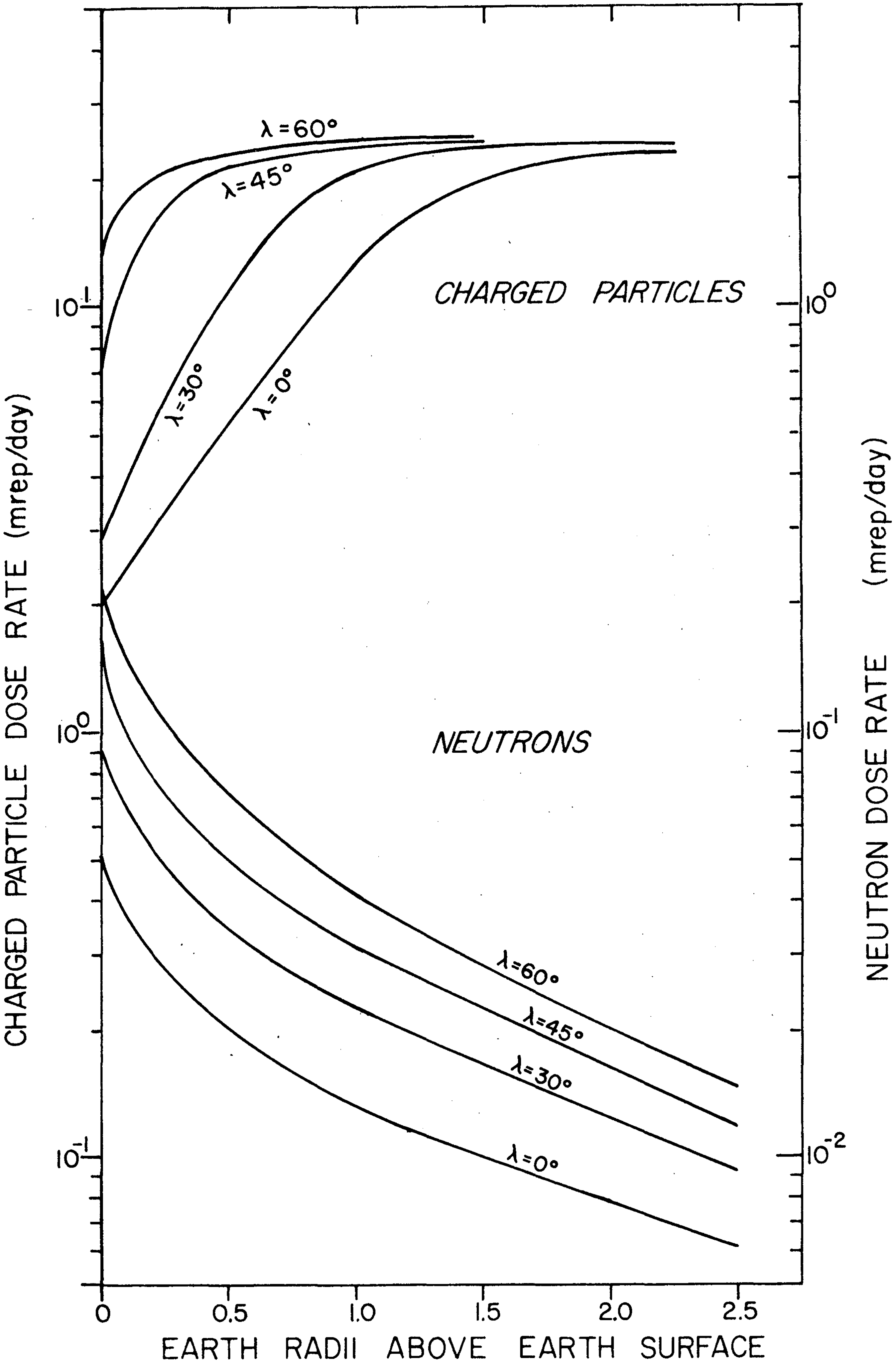
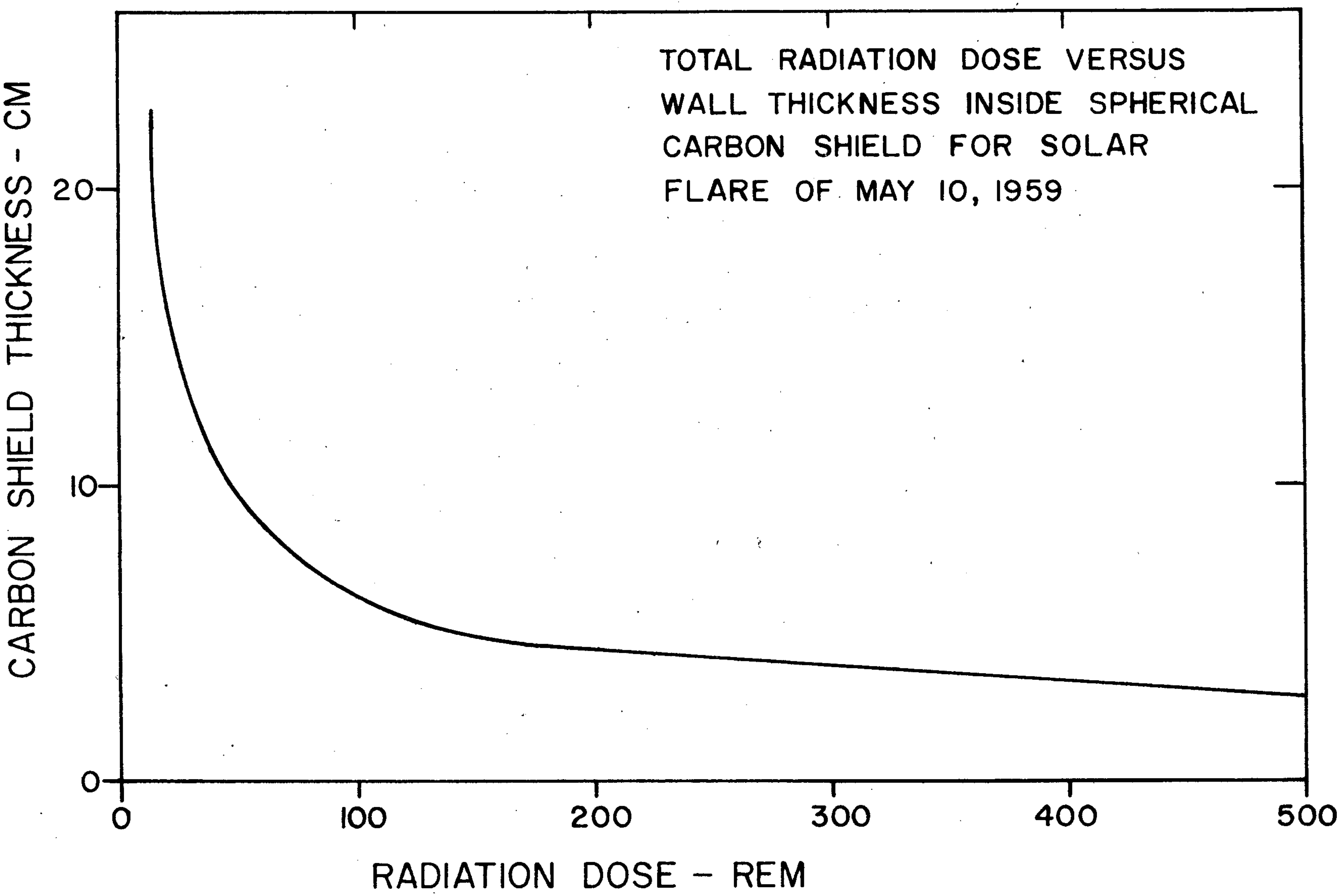

λ=60°
λ=45°
λ=30°
λ=0°
CHARGED PARTICLES
NEUTRONS
λ=60°
λ=45°
λ=30°
λ=0°
CHARGED PARTICLE DOSE RATE (mrep/day)
NEUTRON DOSE RATE (mrep/day)
10^{-1}
10^{0}
10^{-1}
10^{0}
10^{-1}
10^{-2}
0
0.5
1.0
1.5
2.0
2.5
EARTH RADII ABOVE EARTH SURFACE

Figure 5.

The wall thickness of carbon necessary to reduce the radiation inside to various rem doses for the solar flare of May 10, 1959, as calculated by Robey.(6) It is very difficult to eliminate the secondary neutrons produced in a thick shield which accounts for the apparent asymptote at about 20 rem.

TOTAL RADIATION DOSE VERSUS WALL THICKNESS INSIDE SPHERICAL CARBON SHIELD FOR SOLAR FLARE OF MAY 10, 1959
CARBON SHIELD THICKNESS - CM
20
10
0
0
100
200
300
400
500
RADIATION DOSE - REM

REFERENCES

1. Harrison Brown, "A Table of Relative Abundance of Nuclear Species," Revs. Modern Phys. 21, 625 (1949).
2. J.R. Winckler, Primary Cosmic Rays, talk presented at the Radiation Research Society Symposium on Radiation in Space, May 10, 1960.
3. S. Fred Singer, "The Primary Cosmic Radiation and Its Time Variations," Progress in Elementary Particle and Cosmic Ray Physics 4, 282 (1958).
4. G. Puppi, "The Energy Balance of Cosmic Radiation," Progress in Cosmic Ray Physics 3, 385 (1956).
5. Hermann J. Schaefer, "Radiation Dosage in Flight Through the Van Allen Belt," Aerospace Medicine 30, 631 (1959).
6. Donald H. Robey, "Radiation Shield Requirements for the Solar Flare of May 10, 1959, "Convair Astronautics Report AE60-0177, February 18, 1960.
7. Seymour T. Nelson, "A Brief Survey of Cosmic Ray Data with Regard to Space Vehicle Protection," Army Ballistic Missile Agency Report DV-TR-2-59, April 15, 1959.
8. B. Peters, "The Nature of Primary Cosmic Radiation," Progress in Cosmic Ray Physics 1, 223 (1952).
9. W. Hess, "Cosmic Ray Neutron Demography," UCRL-5899, March 1, 1960.