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INTRODUCTION

The several sources of radiation which one expects to encounter in the course of space exploration fall into five categories.

A. The most energetic radiations are the normal cosmic ray background, often referred to as galactic cosmic rays. These have been known for more than 50 years and their characteristics are fairly well understood.[1] Fortunately, in spite of their very high energies, their intensity is sufficiently low so that the dose one would expect to receive from them, even in an unshielded space ship, is quite small. These primary or galactic cosmic rays are divided naturally into two types, the lighter component consisting of protons with energies extending in some rare cases up to well over 10^{18} electron volts, and heavier ions such as He, Li, Be, B, C, N, O, F, and several other ions up to iron have been identified. Lithium, beryllium, and boron, although quite low in intensity, definitely are present in the primary cosmic rays.

B. The second natural category can be referred to loosely as solar cosmic rays These are more recently discovered than the galactic cosmic rays, their existence having been carefully investigated only since 1956. They are quite variable in their intensity and are produced in conjunction with visible outbursts from the sun. They probably constitute the most serious natural radiation problem in space. The majority of this report deals with them.

C. The third natural category is the Van Allen radiation, which is fairly intense but quite localized in space. This limited region consists of one or two belts circling the earth and symmetrical with respect to the equatorial plane of the magnetic field; it extends from 400 to 40,000 miles above the surface. For a space ship orbiting inside the Van Allen Belt or passing through the belt twice in every orbit the radiation encountered would be fairly intense. Because the belt may be rather easily avoided it is not a major problem for lunar or planetary travel, as was once feared.

D. The fourth possible source of radiation provides strictly an engineering problem. It is the radiation produced by nuclear reactors that might be carried in a space ship. The shielding criteria for such reactors have been voluminously documented in the literature in connection with the nuclear airplane project. There is in space no air scattering around the shield to complicate the direct shielding problem; therefore, no particularly new aspect is introduced by space travel, with the possible exception that in space it might be practical to separate the crew from the reactor by a greater distance than in the airplane.

E. There may be other sources of radiation as, for example, the surface of the moon or planets. There is no evidence at present that the surface of the moon contains unusual levels of radioactivity. At this time all the planets are beyond our ability to make direct measurements of surface activity.

In general it seems that the radiation danger is quite small for lunar trips lasting 1 to 3 weeks. The radiation problem is somewhat more severe for extended trips such as to Mars or Venus, on which the space ship will inevitably be exposed for periods of many months. Unfortunately it is not possible with the information now at hand to state categorically whether this is a serious problem or only an irritating one. Quantitatively small changes in dose measurements might push the conclusion either way. It is the object of this paper to bring together in a brief form as many presently available facts as possible to allow evaluation of this situation as the new data become available.

PRIMARY COSMIC RAYS

Primary cosmic rays have been investigated for many years and there is a vast body of literature on the subject. The synthesis of these many different reports has led to a fairly consistent picture, which indicates that the primary or galactic cosmic rays with which the earth is constantly bombarded are of extrasolar origin. There is a factor-of-2 change in their intensity during the 11-year solar cycle. They are twice as intense at the minimum of the solar cycle--that is, when the solar sun spot count is at its minimum value. This factor-of-2 change, which has been observed for many years, is interpreted as caused by a change in the sun's magnetic field, the solar field being stronger at times of solar sunspot maximum. The increased field protects the earth from the galactic cosmic rays. The magnetic field dwindles during the minimum of the solar cycle and consequently the intensity of cosmic rays reaching the earth increases.

With the exception of this solar-induced variation of the galactic cosmic rays we find that they are remarkably constant and have been so during the last 50 years. There is some experimental evidence that they have been constant for several hundred thousand years. They are thought to be of galactic origin--possibly from supernovae in the galaxy, or possibly from some synchrotron type of acceleration mechanism--or to be the result of an approach to an equilibrium energy distribution between charged particles and magnetic clouds. These several theories of their origin have been suggested principally by Enrico Fermi.

There is no general agreement about the origin of cosmic rays; however, several outstanding facts about the primary cosmic rays must be taken into consideration in any theory of their origin, and in the evaluation of their possible biological effect. Their energy spectrum is given roughly by

$$P(E>E_t) = 0.4\ E_k^{-1.15}$$

The similarity of the spectra of the various major components of the primary cosmic rays suggests that the protons, deuterons, alpha particles, carbon, nitrogen, oxygen and heavier ions have all been accelerated by the same mechanism in such a way that, although their spectral intensities vary with the type of ion, the energy dependence of their spectra is quite similar. This similarity of spectral shape rules out some of the theories of the origin of cosmic rays and indicates that some of the acceleration mechanisms proposed for their origin are not realistic. Although the most likely source of cosmic rays is not yet agreed on, it is very tempting, in view of the similarity of the energy spectra, to feel that a gross accelerating mechanism carrying along all atomic species in a shock wave or plasma bundle, as in an exploding supernova, may offer a logical explanation. Fortunately for our purposes the understanding of their origin is not particularly critical.

The spectra given in Figure 1 are extrapolated to locations in space more than 10 earth radii away where the effect of the earth's magnetic field is negligible. The dotted lines in the figure, labeled with latitudes of the earth, refer to the fact that the net result of the earth's magnetic field acts on primary cosmic rays to prevent cosmic rays below a certain cutoff energy (a function of latitude) from reaching the earth's surface. At the earth's magnetic poles in Northern Canada and Antarctica there is no so-called energy cutoff, and cosmic rays of arbitrarily low energy can penetrate to altitudes of roughly 100,000 feet or lower, barring their encounter with atoms of the air. The energy spectrum at the magnetic poles is thought to be characteristic of that in free space, but spatial orientation of the cosmic rays is directed vertically rather than in the 4-π free-space orientation. With regard to their free-space orientation, no preferred direction for cosmic rays has ever been discovered, although the earth's magnetic field somewhat distorts the apparent direction of approach of cosmic rays. When corrections are made to eliminate the effect of the earth's magnetic fields it seems that the primary cosmic rays are probably isotropic in the solar system.

As a result of the energy cutoff and the resulting inability of cosmic rays with less than a certain energy to reach the surface of the earth, there is a shift with latitude of the energy spectrum observed at the top of the atmosphere or at the surface of the earth, because the earth's magnetic field extends to about 10 earth radii or about 40,000 miles, but the earth's atmosphere extends only to about 20 miles. The spectral situation at the top of the atmosphere is essentially that which one would have at the surface, if the earth's atmosphere did not exist but only the magnetic field were present.

Particles arriving at the geomagnetic equator, which roughly parallels the geographic equator, must have momentum of about 14 Bev/c in order to penetrate to the top of the atmosphere. At 30° geomagnetic latitude this value has declined to about 7 Bev/c; at 60° latitude it is only 1 Bev/c, and it goes to essentially zero at the geomagnetic pole. This phenomenon is most convenient for investigating the primary cosmic rays, because merely by making measurements at the top of the atmosphere (or, under special circumstances, at sea level) at different latitudes one can investigate the spectrum of the primary cosmic rays. This technique also applies to the particles associated with solar flares. If sea-level measurements are made, the atmosphere unfortunately introduces secondary particles that tend to mask the effect and to make the interpretation more difficult.

This magnetic effect on cosmic rays, which directly influences space travel only inside the Van Allen belts, is a basis for much of our understanding of the cosmic rays. It can be explained by noting that the earth's magnetic field is shaped about like the field of a bar magnet or dipole magnet located approximately at its center. The center of this equivalent magnet is located about 342 kilometers from the center of the earth, and its magnetic poles at latitudes of 80 degrees north and 76 degrees south, rather than at 90 degrees in each case. All magnetic effects are tilted in such a way that the magnetic latitudes over the entire North American continent are somewhat higher than its corresponding geographic latitudes.

Another result of the magnetic field is that positive particles of low momentum

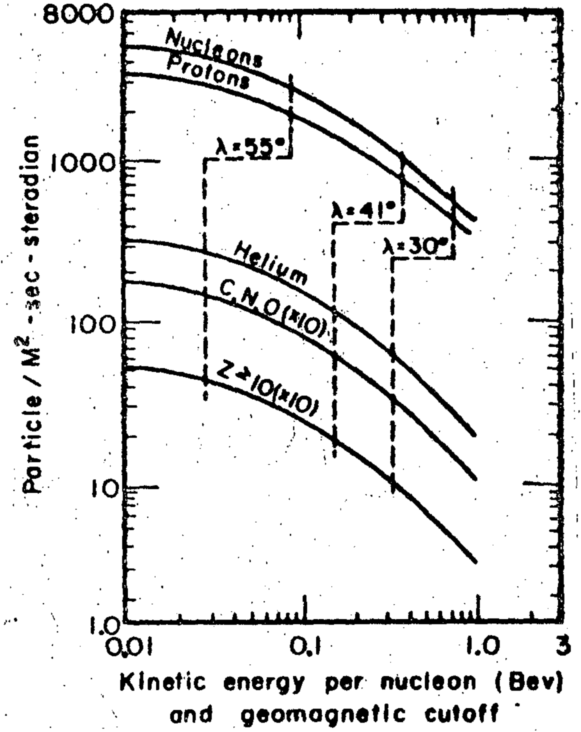

Figure 1. Integral energy spectrum of primary cosmic rays, separated into four constituents: nucleons as a whole; protons; helium; carbon, nitrogen and oxygen and $Z \geq 10$. The magnetic cutoffs for 30, 41 and 55 degrees geomagnetic latitude are shown. The cutoff at the equator for protons is 15 Bev. After B. Peters (ref. 1).
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at any particular longitude reach the earth more easily from the west than from the east. These directions are interchanged for negative particles, the so-called "east-west" effect that is the basis for our belief that essentially all primary cosmic rays are positive in charge. This does not mean that the earth has gradually accumulated an enormous net positive charge. There is a simultaneous flow of negative electrons to the earth which exactly balances the flow of positive charge to the earth. These electrons, however, have quite low energies compared with the energies of positive cosmic rays, and the major energy flow to the earth is carried by the positive, heavy cosmic rays. The spectral shape for charged particles is unaffected if the particles have sufficient energy to penetrate the earth's magnetic field. The spectra are "cut off" at their low-energy ends by the excluding effect of the magnetic field.

Figure 2 shows the relation between primary cosmic-ray intensity and distance from the earth at four different latitudes. This intensity rises to an asymptotic value of about 26 millirep per day at distances greater than 2 to 3 earth radii, and that at such distances the effect of the earth's magnetic field, in causing intensity variation with latitude, becomes very small. The dose rate of 26 mrep per day is that which would, in the absence of solar flares or other special situations, be received by an astronaut at large distances from the earth, for example, in the main cockpit of a space vehicle or on the surface of the moon or some other planet such as Mars. There is some question as to the proper RBE factor to be applied here to give this irreducible radiation dose in units of rem per day. It seems probable, however, that a reasonably small RBE factor, between 1 and 5, would be appropriate. This would mean that there would not be a serious radiation problem

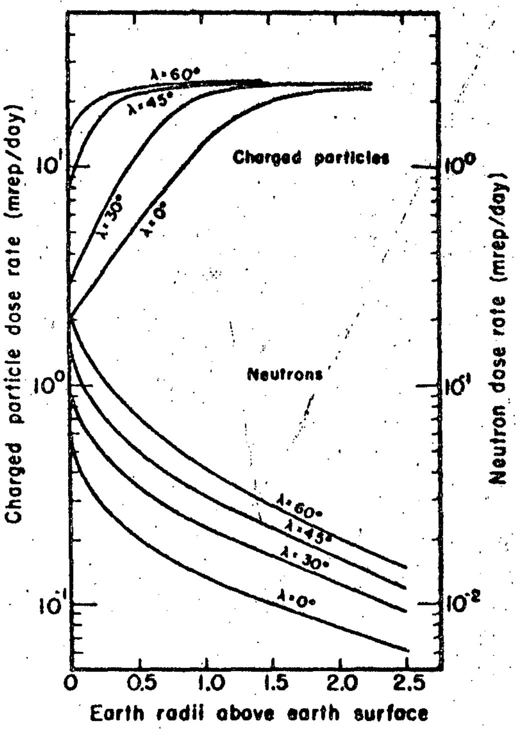

Figure 2. Dose rates in mrep/day for charged cosmic rays and for secondary neutrons escaping from the atmosphere. Note that the neutron curves have been shifted up by one cycle for compactness. From Wallace (ref. 6).

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involved in extended residence outside of a special solar flare shield at times when flares are not occurring.

The earth acts as a perfect cosmic ray absorber: no cosmic ray (except for neutrinos, which are not important to our considerations) is sufficiently energetic to pass through the earth. As a result of this shielding effect, the cosmic ray intensity at any point relatively near the earth is cut in half. This presumably is also the case near all other astronomical objects. The constant counting rate measured by the Russian rocket as it approached the moon in 1959 indicates that the radiation near the lunar surface is about one-half due to cosmic rays and one-half due to radioactive content of the lunar surface.

A great deal of experimental and theoretical work has been done on the secondary cosmic radiation particles knocked out of the air by the passage of the primary cosmic rays. Because the incident primary cosmic rays are largely absorbed at altitudes above 70,000 or 80,000 feet, these secondary cosmic rays are the principal ones available to surface investigators. The large amount of information available on these secondary radiations, which consist of protons, mesons, electrons, photons and neutrons, indicates that they do not constitute a serious dose hazard on the earth and would not under any other planetary atmosphere. Therefore we should concentrate our present attention on other types of radiation, which are observed largely in the vacuum outside our atmosphere, and neglect any further discussion of the production of secondaries in a planetary atmosphere.

SOLAR FLARES

Solar flares, although a relatively recent discovery, have been described by a number of authors, and summarized by several, as in the excellent review article by D. H. Robey.[2] In discussing the phenomena of solar flares a few words should be said about the sun itself and about the much more fully observed phenomena of solar sunspots. A few simple facts about the sun will be of value in our discussion. The sun rotates on its own axis in the same manner as a planet but much more slowly, the period of rotation being 27 days. The sun has its own magnetic field, which in an overall average at the solar surface is somewhat weaker than that of the earth; however, the local magnetic field strengths are often in the kilogauss region. The visible surface of the sun, called the photosphere, is a highly absorbant layer of incandescent gas and is the source of most of the visible radiation. It is the photosphere that emits the radiation received by the earth, which is similar to that which would come from a radiating black-body at 6000° Kelvin.

The blackbody concept cannot be extended to the short-wave-length end of the spectrum, because a negligible amount of radiation is emitted below 1500 Å. The 6000° blackbody analogy is good only near the visible region. Of interest in the prediction of solar flares are two extremely intense emission lines in the short-wave-length end of the solar spectrum, the hydrogen and alpha line at 1216 Å and the doubly ionized helium line at 304 Å. Neither can be seen at the surface of the earth because essentially all wave lengths shorter than 2850 Å are absorbed by the earth's atmosphere. Actually the intensity of the hydrogen alpha line at the distance of the earth from the sun amounts to a few tenths of a microwatt per cm^2. It is the most intense line in the entire solar spectrum. The solar corona seen during solar eclipses as a bluish-white halo with a greenish cast extending several million miles out from the sun, should not be confused in one's thinking with solar flares. The solar corona is an extremely low-pressure gas which has a temperature of approximately 1,000,000° K, which is required to account for the expansion of the corona against the pull of the sun's gravitational field. The greenish tinge is apparently caused by iron atoms each of which has lost 13 electrons. The light from the corona does not have strong lines in it because the very high velocities of the atoms produce Doppler broadening of the spectral lines.

The Solar Wind. There is an important phenomenon known as the solar wind that has received attention only in recent years. It consists of ionized hydrogen atoms which continuously fly away from the sun in all directions. These form an electrically neutral plasma which is completely ionized and has as a result its own "frozen" magnetic field. It is apparently a consequence of this plasma streaming that the sun's otherwise dipole magnetic field is considerably flattened into a disc shape. The velocity of the solar wind is a few hundred to a few thousand kilometers per sec. The particle density ranges from 10^{-2} to 10^2 ions/cm^3 at the earth's orbit. On at least one occasion there was a sixfold increase in the velocity of the solar wind as measured by Explorer X at a great distance from the earth several hours prior to a solar flare. There was an accompanying disturbance of the sun's magnetic field which ordinarily is between 20 and 32 gammas (1 gamma = 10^{-5} gauss), so it is possible that the solar wind and the accompanying magnetic field bear some relation to the impending onset of a solar flare.

The solar wind seems to carry the sun's distorted dipole field radially outward to a distance somewhere between the orbit of Mars and the orbit of Jupiter. In this region the magnetic field is sufficiently weak to equal roughly the galactic magnetic field. At this radius there is a disturbed field configuration. Several measurements have indicated that solar flare particles released from the sun are fairly well contained within a roughly spherical region whose perimeter lies somewhere between the orbits of Mars and Jupiter, because this barrier is known to reflect very energetic particles emitted by the sun. It is conceivable that the Martian-Jovian boundary may screen the earth from some external galactic cosmic radiation. However, no direct measurements of this possibility are at present available.

The average magnetic field on the surface of the sun seems to be 1 gauss and this value falls off roughly as the inverse square of the radius for considerable distances from the sun; only outside the earth's orbit does it seem to be of conventional dipole inverse cube behavior.

The sun is known to be a source of soft X rays which are emitted both by the corona and by the photosphere. The X-ray emission changes rather rapidly in both intensity and wave length. In some cases, for example, a hot spot in the corona may last for an hour and during this time increase the radiation of 8-to-20 Å wave length quite markedly. It has been observed that when a solar flare occurs, the total X-ray energy output may be as high as 10^{31} ergs, which represents 7000 ergs/cm^2 at the earth's distance from the sun. This X-ray emission may last for 30 minutes. It is relatively easy to shield against these soft X rays which apparently do not constitute a serious hazard.

Sun Spots. Sun spots are characterized by the sunspot number, R, which is a measure of sunspot frequency. It was first defined by R. Wolf of Zurich in 1849 as the number of sunspots, n, on the solar disc which appear in g groups, and the sunspot number is

$$R = K\ (n + 10\ g)$$

where K is an estimate of the local observing conditions (Figure 2). K is about 0.6 for Zurich. R would be 1 for a telescope in free space. The relative sunspot numbers for a period of more than 200 years are shown in Figure 3. Interestingly, the recent year 1958 had the highest number on record, when 910 sunspot groups were observed from Mt. Wilson in California. The sun was visible for 339 days during this year. The average time between peaks in the sunspot intensity curve is 11.1 years; however, variations as much as 3 or 4 years from this value have been known. There is also 90-year periodicity, which is superimposed on the 11-year period. We were at the peaks of both cycles in 1958.

Sunspots themselves occasionally can be seen with the naked eye through a dense absorbing filter. When studied in detail with a telescope they usually appear in pairs. Because their temperature is 1000° to 2000° lower than the 6000° average temperature of the surface, they have a somewhat darker appearance than the surrounding photosphere. Many of their characteristics are known. For example, there is an area surrounding the spot itself which appears to be covered by radial filaments. These filaments change with a lifetime of about 30 minutes. The spots themselves are shallow bowl-shaped depressed areas ranging in diameter from 150 to 50,000 miles. Several spots may overlap, forming patches as large as 150,000 miles across. Ordinarily a spot lasts only a few days, although some individual spots

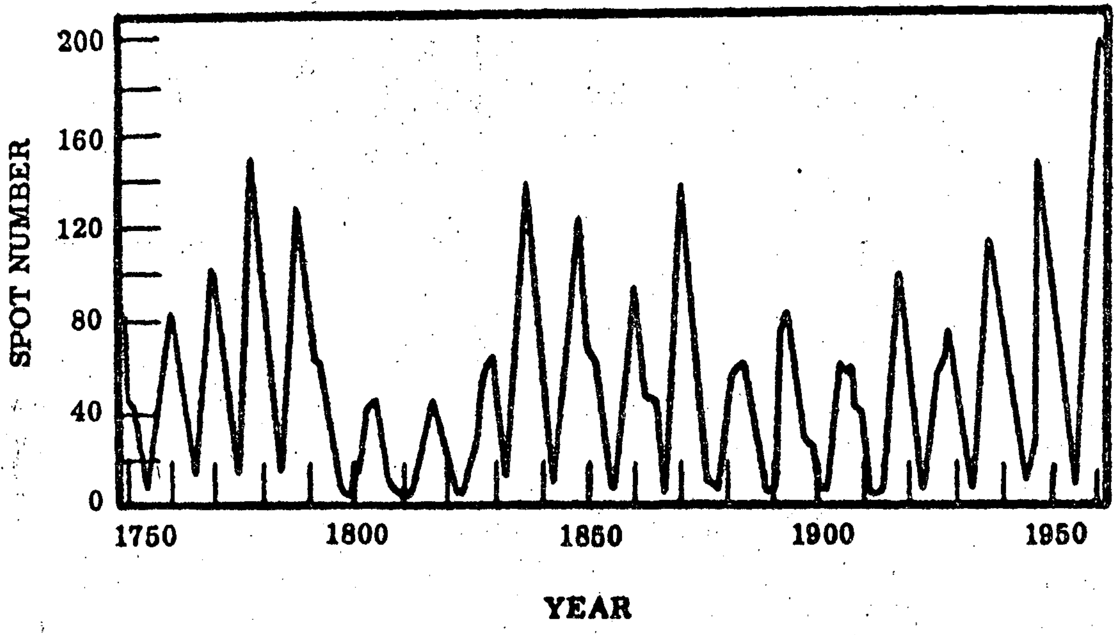

Figure 3. Relative sunspot number versus time, showing the short-period (11-year) and long-period (~90-year) solar cycles. From D. H. Robey (ref. 2).

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have lasted for months.

Sunspots normally appear in groups that are elongated along latitudes of the sun, and they appear in zones both north and south of the solar equator. Most spots confine themselves to the region between 8° and 30° north and south latitude. They rarely come within less than 8° of the equator. Each 11-year cycle begins with the groups of spots located 30° north and 30° south of the equator. The succeeding groups gradually appear closer to the equator, fading out at about 8°.

The spots are magnetically polarized and the polarity reverses itself on succeeding solar cycles, so that there is a polarity cycle of 22 years. The large magnetic field of sunspots is apparently important in maintaining the temperature differential between them and the surrounding area. Many other phenomena of solar sunspots have been observed which indicate that in general they are strongly magnetic regions. They are related to each other in groups in turn related to the rotation of the sun, the phase of the solar cycle and the internal magnetic structure of the sun. Some knowledge of the qualitative behavior of the sunspots is perhaps of value in our subsequent discussion of soler flares. A small sunspot is likely to have a magnetic field of the order of 1000 gauss, which is greater by three orders of magnitude than the average solar magnetic field. The large groups may have magnetic field strengths extending up to 4000 gauss. The magnetic field of a spot tends to extend vertically along the solar radius.

<u>Solar flares</u>. Although magnetic storms observed on the earth have been correlated with large sunspots, it is more likely that they are caused by solar flares. When a flare is seen in profile on the limb of the sun it usually resembles a bright little mound directly above the photosphere. Loop prominencies are often seen in

conjunction with flares, and it is possible that they may represent the ejected flare plasma, which can be seen only near the limb of the sun. Most flares are red because they emit large quantities of hydrogen alpha light at 6562 Å. Occasionally a flare is sufficiently intense to be seen as white light. Usually they are best observed through a band-pass filter about a 2 Å wide that includes the hydrogen alpha line.

A typical flare is thought to consist of two phenomena, an expulsion of low-velocity particles contained in a magnetic capsule that take about a day to arrive at the earth, and prompt particles that travel along curved paths from the sun at about 60% of the velocity of light and are observed earlier than the low-velocity particles, but which do not themselves produce magnetic storms. However, these high-velocity particles are responsible for polar-cap blackouts, which are described later.

The bowl-shaped solar prominence associated with the flare may be as high as 20,000 kilometers above the photosphere surface; 10,000 kilometers is usually an upper limit, however. A flare can cover as much as 0.1% of the sun's surface. They are rarely seen more than 10,000 kilometers from the center of a sunspot group. Shortly after or at the same time as a flare starts, some of the surface region of the sun around the flare brightens considerably. At the same time the tenuous hydrogen clouds that frequently float above the photosphere and are occasionally seen in profile, may temporarily brighten or vanish. This phenomenon occasionally occurs with no accompanying effect on the filaments, which are also above the solar surface but at a lower altitude than the hydrogen cloud, and this is interpreted to mean that the disappearance of the hydrogen cloud is not the result of direct radiation from the flare bowl to the clouds but rather of the movement of ions along curved magnetic flux lines, thus avoiding the intermediate filaments.

It seems reasonable to assume that the energy contained in a flare comes from the magnetic field associated with the sunspots that surround it. The exact mechanism by which this is accomplished is not clear. The sunspots associated with flares are usually rather complex and disordered and their magnetic field somewhat nonsymmetrical. The flare usually arises in a null field position where the gradient of the field is quite steep but its absolute value perhaps near zero. In a typical large flare, an energy release amounting to 10^{32} to 10^{33} ergs may result from a rapid change in the magnetic field in this region.

The fraction of total flare energy that goes into X radiation, hydrogen alpha light, radio noise, auroral displays and, most importantly, cosmic rays is now known. For the largest flare on record, that of February 23, 1956, it has been estimated that about 1% of the total energy of 3×10^{32} ergs went into protons with energies above 2 Bev, and approximately 0.6×10^{32} ergs of hydrogen alpha light was produced.

The particles ejected in conjunction with flares are probably between 85 and 100% protons. Other particles have been detected, including heavy ions, but these are not particularly numerous. If neutrons were released by flares, then in view of their nonmagnetic behavior they would be predominantly observed at the solar noontime position on the earth. Such is not the case, and it is consequently presumed that the mechanism for solar flare production is not a nuclear process. The neutron half life of 13 minutes certainly considerably reduces the flux at the earth of any neutrons that might be emitted by the sun, because flight times from the sun to the earth at least as long as the half-life are involved for high-energy neutrons. Neutrons have not been detected in solar flares, which indicates that neutron doses would not be a problem in conjunction with solar flares.

Actually, Severnyi has identified 25 different elements in the optical spectrum of solar flares.[3] How many of these are accelerated is not known, but some heavy ions have been detected in satellite experiments.

Bright shock waves have been seen moving out from flares at supersonic velocities. When these supersonic shock waves approach a sunspot they are somewhat retarded, their luminosity increases and they appear to follow curved magnetic channels. Sometimes these phenomena are accompanied by accelerations of the solar atmosphere which appear to be operating against the gravitational effect. In spite of the failure to observe neutrons, deuterium lines are often observed as intensified, showing that neutrons actually may be produced as a by-product of the flare. In evaluating the possible mechanisms for solar flares, it should be remembered that the ionization of the gas in which they occur is extremely high and that as a result the magnetic field is frozen into this solar plasma. Under these conditions it is not possible for large electrical currents to flow, because such currents would require a magnetic field reorientation. As a result, when a blob of solar plasma is ejected from the sun, it carries along trapped within it the magnetic field that was originally present in this particular mass of gas.

The initial explosion of a flare produces X rays which are apparently simultaneous with the visible hydrogen alpha light flash and have energies as high as 100 kilovolts. These produce sudden ionization of the D region of the upper atmosphere and also force the D layer to a lower altitude, especially in the polar cap region. A flux of high-energy protons may accompany this initial photon flux and lasts for an hour or more. The proton flux then decays in a manner that suggests that the protons may have been trapped in a large but leaky magnetic bottle partially closed by magnetic mirrors at each end.

At the earth the flux density of these protons has been known to reach two or three orders of magnitude above that of the average galactic cosmic ray flux. As mentioned previously, a low-energy magnetized plasma arrives at the earth about one day later. The average transfer time is about 33 hours. This low-velocity plasma that follows a day later behaves in a manner suggestive of the behavior of a shaped-charge jet produced by a chemical high explosive, where there is an initial outburst of material followed later by a large mass of material. The protons in this late-arrival plasma cloud are of relatively low energy; however, the magnetic field that it contains strongly influences the magnetic field of the earth, producing magnetic storms and intense auroral displays. The low-energy proton-containing plasmas which can induce geomagnetic storms do not seem to accompany flares of class less than 2.

Flares are classified according to the limits set forth in Table 1. We are principally concerned with flares of classes 3, 3+, and 4. Actually only flares of class 4 seem to be particularly dangerous to an astronaut with a minimum of shielding. Dangerous solar flares are generally accompanied by radio-wave reception. There are several different types of radio emission associated with solar outburst phenomena; they are outlined in Table 2.

Type II and type III solar radio noise outbursts, although not always present, often signal the initiation of a solar flare. Type II radio noise, that tends to

Table 1

FLARE CHARACTERISTICS*

Class	Number of flares (1959)**	Duration in min.	Relative intensity (H-alpha)	Mean area 10^{-6} visual hemispheres	Average H-alpha line width, Å	Maximum particle energy
1-	2209	5-20	1.5	≈25	1.5	
1 123 1+ 9	132	4-43	1.5	100-250	3.0	
2 21 2+ 6	27	10-90	2.0	250-600	4.5	
3	6	20-155	2.5	600-1200	8	several hundred Mev
3+	1	50-430	3.0	1200	15	1 Bev
4	0.02***	44-120	4	1200	23 or greater	2 to 40 Bev

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*After Robey (ref. 2).

**The data in the second column are based on the measurements by G. E. Moreton of the Lockheed Solar Observatory (2375 flares during 1869 hr of observation).

***Based on eight class-4 flares in a 20-year period.

Table 2

NONTHERMAL SOLAR RADIO NOISE*

Type	Duration	Source	Speed through corona (km/sec)	Spectral character	Band width
I Noise storm burst	20 sec	"R" center	----	nearly fixed, narrow	a few Mc
II Outbursts excited by gas motions through the corona	minutes, 10-100 per hour	flare, limb ejections	1000 km/sec	slow-frequency drift to lower values, sharp cutoff	broad with narrow peaks, tens of Mc
III	seconds	initiation of flare	10^5 km/sec or more	fast-frequency drift to lower values	5-1000 Mc
IV Synchrotron radiation	several hours	occurs after flares	stationary after type II motion	spiraling electrons 100% polarized	continuous distributions 15-1000 Mc
V	minutes	often flare	3000 km/sec after type III motion	100 Mc region	tens of megacycles

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*After Robey (ref. 2).

be associated with magnetic storms, is also associated with class 2 or class 3 flares. More than 90% of these slow-drift bursts were associated with flares of importance greater than 1. Conversely it can be said that all flares that have radio noise associated with them have either a group of type III bursts, or a type II burst followed by a type III burst.

The type II burst may be delayed as long as one minute after the optical onset of the flare, but it still provides ample warning of imminent arrival of the charged particles. The type IV noise is highly correlated with the solar flare particles, but comes too late to provide advance warning of the flare. The flare particles themselves provide several minutes of advance warning, and although the rate of rise of the flare radiation is quite steep, a man would be quite safe to rely on his radiation detectors to tell him when to take cover.

It is interesting to note that the number of sunspots occurring in the northern and southern solar hemispheres is approximately equal, but that sunspots in the northern solar hemisphere are about 6 times more likely to be associated with intense flares than are those in the southern solar hemisphere. This ratio is based on a 23-year study of 580 major solar flares. About 60% of these flares originated from spot groups located within 20° longitude of the central meridian as viewed from the earth. A plot of solar flare locations as a function of their magnetic type is shown in Figure 4,[2] and these data are summarized in Table 3.[2] Spots of the type $\beta\gamma$, that have a complex magnetic field and that are located in the northern hemisphere, are far more likely to produce flares (Table 3[2]). Actually none of these complex spots was identified in the southern hemisphere. Once a flare has occurred a "magnetic channel" appears to have been formed from the sun to the earth down which the flare particles pass. Some hours later this same channel from sun to earth conducts the low-energy plasma responsible for geomagnetic storms and auroral displays.

The character of the type III radio noise is somewhat altered by the superposition of harmonics thought to be caused by oscillations of the solar corona as the charged flare particles pass outward through it. This is a well-known effect in plasmas. The harmonic alteration of type III radio noise signals is thought to be a clear indication of the ejection of protons from the sun.

Table 4,[2] that lists the great solar flares, their points of origin on the sun and their subsequent geomagnetic activity, shows that there is an overwhelming preponderance of major flares located in the northwest quadrant of the sun, an effect thought due to the shape of the sun's magnetic field. The solar magnetic field is flattened in the plane of its equator by the conductivity of the solar winds into an inverse-square-law dependence. This solar-wind interaction with the sun's solar magnetic field produces also a spiraling of the radial field lines toward the west. The sun rotates in the same sense as the earth proceeds around the sun, so that on our side of the solar disc the apparent motion is from left to right (from east to west), and the solar magnetic flux lines approach us from the west of the sun. Therefore, the apparent source of particles approaching the earth and spiraling along solar flux lines is 40° west of the sun. This effect also strongly increases the probability that a flare on the west side of the sun will deliver particles to the earth. We view the sun from the west magnetically, or put another way, the solid angle for a solar-flare particle to reach the earth is much larger for events on the west side of the sun than on the east side. Statistical analyses have been made

Table 3

GEOMAGNETIC STORM FLARE DATA*

Magnetic sunspot type	Number of GSPF per 580 flares** N(north)	S(south)	Ratio N/S	Probability of GSPF/spot north	south
Unipolar - α	1	7	0.14	0.00172	0.0121
Bipolar - β	11	1	11	0.0190	0.00172
Semicomplex - β	31	0	∞	0.0534	0
Complex -	18	2	9	0.0310	0.0034

*After Robey (ref. 2).

**GSPF = great-storm-producing flares.

Table 4

SOLAR COSMIC RAY FLARES

Date	Magnetic type of associated spot	Disk position of flare	Subsequent geomagnetic activity
1942 Feb. 28		4° E 7°N	great storm
1942 Mar. 7		90° W 7°N	small storm
1946 July 25		15° E 22°N	great storm
1949 Nov. 19		70° W 2°S	no storm
1956 Feb. 23		80° W 23°N	great storm
1960 May 4		90° W 12°N	moderate storm
1960 Nov. 12		10° W 12°N	very great storm
1960 Nov. 15		50° W 25°N	great storm

*After Robey (ref. 2).

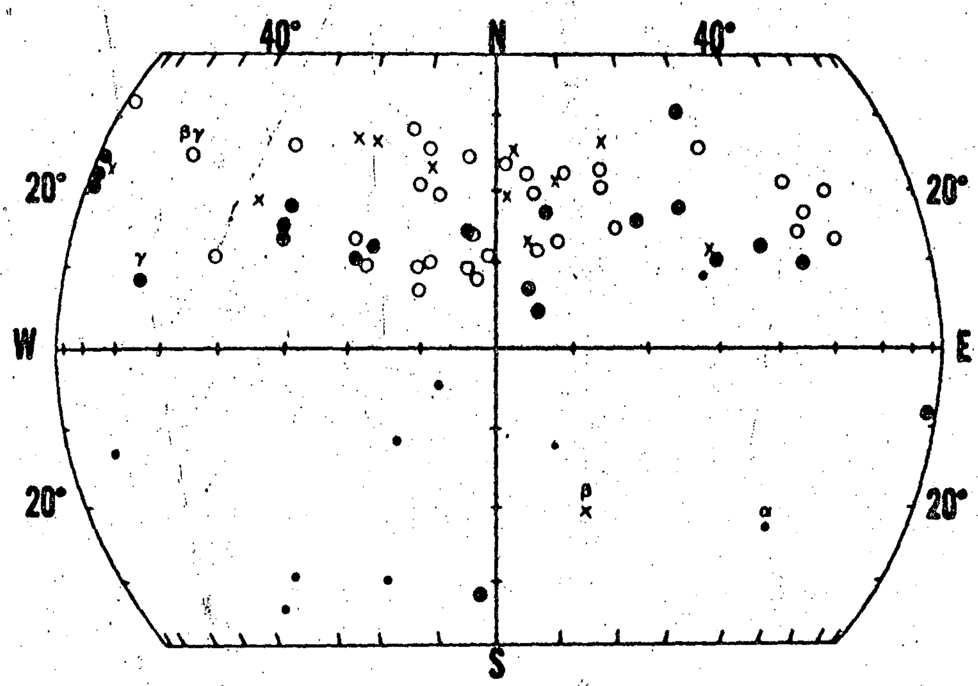

Figure 4. Positions of intense geomagnetic-storm-producing flares on the solar disk. The associated sunspot magnetic field type is also indicated. After Robey (ref. 2).

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of the solar sunspot frequencies and solar flare frequencies, that are closely correlated. However, predictions from one solar cycle to the next are very poor. For example, in 1959, two years after the peak of the cycle in 1957, the sun was still more active than in 1947, the peak of the preceding cycle. Although solar radio noise outbursts are so far not useful for predicting flares in advance, a noise outburst accompanying a flare is a good indication that particles have been ejected. Many flares, with associated radio noise, are observed although the earth does not subsequently receive particles.

A few hours prior to a major flare the region surrounding an associated sunspot group takes on a chaotic appearance, the so-called "ripe look", which an experienced solar observer can identify as having a high probability for emitting a solar flare. Unfortunately these criteria are difficult to describe objectively, the prediction being purely an art on the part of the solar observer. A sunspot or sunspot group that has already produced a flare has a much higher probability of producing subsequent flares, and it should be continuously watched even after it returns from having been on the far side of the sun for the 14-day half-rotation time.

Some general conclusions can be made about solar flare occurrence: flare probability is in phase with the solar cycle, although some large flares have been observed during times of solar minima; during a year there is a higher probability that flares will occur near the equinoxes than that they will occur during June or December. The critical fact in accounting for this phenomenon seems to be that the earth passes through the plane of the solar equator on June 5 and December 5. (This transit is of course not the same as the equinoxes, when the sun crosses the plane of the earth's equator.) Apparently the probability of solar flares is enhanced when we view the sun from as high or as low a solar magnetic latitude as possible. The monthly distribution of particle-producing flares is closely correlated with the geomagnetic and the auroral events of that particular month. These qualitative conclusions suggest that December or June is a better choice for lunar trips of a few weeks than the spring or fall.

If at any time the solar disc contains a small number of sunspots, or if the sunspots are of the magnetic type, age or size having a low correlation with known flare production, it would seem that for the next week or two the probability of encountering a serious flare is relatively small. Apparently advance solar-flare predictions for short lunar trips are entirely within the realm of possibility. Purely on a statistical basis one can say that favorable launching dates can be recognized provided the trip is of sufficiently short duration that the solar conditions are unlikely to change during that period.

It should be noted that in all our discussions we are considering only the near side of the sun. Apparently there is a very small chance that flare particles ejected from the back side of the sun can reach the earth. Actually, out of all the flare events observed there is only one rather doubtful case in which particles came to the vicinity of the earth with no visible flare on our side of the disc. Thus as soon as a spot of known activity swings past the solar limb to the far side we can be reasonably safe from it.

Chupp, Dye, Marr, Oncley and Williams have made an expert analysis of the seriousness of the solar-flare proton radiation hazard.[4] This analysis is based on a statistical approach by which the flares from 1956 to 1960 were taken into consideration and estimates made of their spectral distribution. These spectral distributions were then converted into doses, assuming that the pertinent dose to be considered is at 4 cm depth in tissue. They made their calculations for unshielded tissue and for tissue shielded by 5 g/cm^2 of aluminum. The 5 g/cm^2 of aluminum is chosen to represent a practical minimum of essential hardware for a space capsule. Two or three times as much shielding consisting of hardware may be provided by a reasonable capsule design.

For the 43 events considered during this period, only six actually gave significant doses. Of these the largest was 150 rad. If these data are to be believed, it seems that for a relatively short flight of about 2 weeks there is a very small probability that a flare would be a serious problem even to an unshielded astronaut. Chupp concludes that the probability of encountering a dangerous dose level in the course of a week's space flight is about equal to the probability of a fatal accident in a week of flying in an operational military aircraft. He further concludes that if advance solar flare prediction is used, this hazard can be further reduced by a factor of 3 on short missions. If, in addition a small amount of extra shielding is included, the dose can be further reduced by a factor of 3 to 10.

Thus it would seem that in comparison with the other hazards of space flight the solar flare problem, although well worth serious consideration, is by no means a limiting factor. It is probably preferable to devote payload to components giving system reliability than to shielding. Figure 5 shows the intensity of flare particle

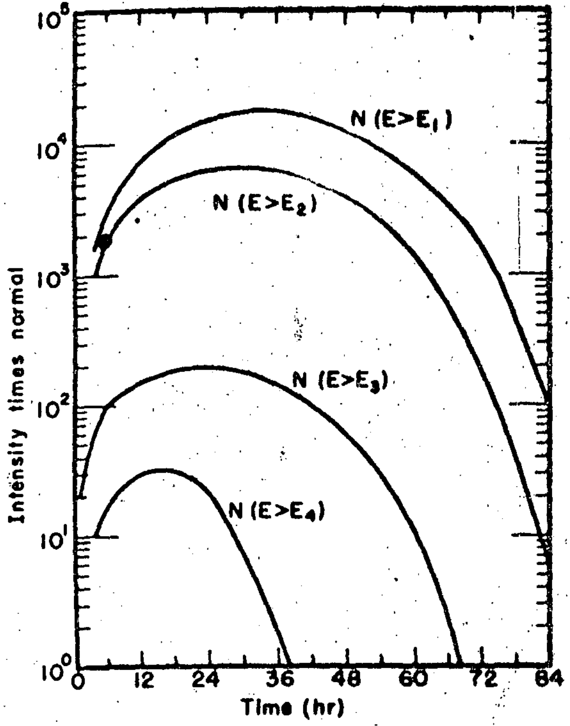

Figure 5. An idealized complete set of curves of integral intensity vs time for Method I. After Chupp et al. (ref. 4).

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radiation in the vicinity of the earth but outside the atmosphere, as a function of the time since the onset of the flare.[4] It is seen that particles of energy $E > E_4$, for example, arrive early and stop early; the low-energy particles--for example, $E > E_1$--arrive somewhat later and persist much longer. Thus there is a shift in intensity with time for particles of a given energy and also for the overall spectral shape. The net result of such a curve tends to be complicated. In terms of dose the dangerous part of a flare certainly occurs during its early phase, because the energies after a few hours usually drop below a few tens of Mev. Protons of these energies are quite easily shielded out by ordinary pressure-vessel walls.

The shift in spectral shape is generally attributed to the different flight times of particles of different energies. The direct flight time from the sun varies by several hours for particles of different energies, and as a result there is considerable dispersion of the originally coherent bundle of particles that were ejected together (within a short time) from the surface of the sun. Unfortunately, each flare differs somewhat from all other flares in its spectral shape as a function of time. Chupp has made some simplifying assumptions in the analysis of the problem in order to secure a numerical answer. For some flares he has assumed that there is a linear rise to the maximum, and that after the maximum is reached the intensity falls off as T^{-n}, where n is fitted to the available time history of the event. The maximum-intensity point is taken to be that one at which riometer maximum is achieved.

"Riometer" stands for relative ionospheric opacity meter. This instrument measures the galactic radio noise received at the earth's surface, a measurement usually made in the polar regions. When the ionosphere becomes more opaque to radio waves owing to the formation of extra ions by bombarding particles in the upper atmosphere ionic layers, the galactic radio background noise is reduced. This is a very simple and effective method for measuring the bombardment of the ion layers of the high atmosphere by particles from the sun. The riometer is especially useful in making measurements of quite low-energy protons, as low as 10 Mev. Such a low energy is quite harmless, because even the thinnest-walled Geiger counters shield out protons with energies less than 30 Mev. The riometer gives a good measurement of the spectrum of protons in the region of a few tens of Mev, which are incident at latitudes greater than 70°. Unfortunately our data on the spectrum of the incident flare protons, especially at energies above 100 Mev, are not as complete as we desire. There are extensive measurements with balloon-borne emulsions, satellites, sounding rockets and even some types of sea-level detectors. The most consistent picture measurements are now supplied by the riometer. The data gathered in other ways are reasonably consistent but show rather wide variations.

The most critical question in all flare measurements arises when we try to predict their spectral shape in a few-tens-of-Mev region in those cases in which the only measurements were at higher energies. This is the case when data for a flare depend largely on sea-level measurements which, because of the magnetic cutoff of the earth's field, are automatically limited to high-energy particles. In these cases the extrapolation from the measured high-energy spectrum to the low-energy spectrum is subject to considerable error, so that rather wide variations are possible in estimates of the seriousness of the dose problem. This has been especially true of the data obtained from some of the large flares of the past. Some methods of extrapolation to lower energies, such as the use of the same energy power law, have predicted colossal doses in the 10-to-100-Mev region. It seems, now that more data are becoming available on the spectrum of the protons in solar flares, that there is less of a tendency to make such linear extrapolations and more of a realization that a nonlinearity of the spectrum tends to de-emphasize the low energies. This places considerably lower estimates on the doses from flares, which it was thought a few years ago would be fatal even under thick shield.

HEAVY IONS

The second most serious and less known radiation problem to be encountered in space travel is that of heavy ions. Heavy ions, as was shown in Figure 1, are present in the primary cosmic rays with spectra whose energy dependence is similar to that of the primary protons.

Heavy ions associated with solar flares were detected in emulsions under about 0.1 g/cm^2 of shielding. This is a very thin shield. The elemental distribution of the heavy ions associated with flares is the same as that for solar material, indicating that they do indeed come from the sun. Their ranges were from 2 to 3 mm in emulsion, which is such a short range that there is certainly no significant radiation problem associated with flare-produced heavy ions. As a result of the apparently very modest energy of the occasionally produced solar-flare heavy ions it seems unlikely that they present a radiation problem that needs to be considered seriously for interplanetary travel.

Heavy ions present a radiation problem in quite another direction, the importance of which is not yet completely evaluated. The heavy ions associated with the primary cosmic rays, although very low in intensity, certainly do have ample energy to penetrate many grams of material. Simons has pointed out that in view of the potential lethality of a few of the largest solar flares, either measures must be taken to protect against them or they must be avoided by some form of prediction.[5] In any event, once these measures have been taken, the radiation dose received by a crew of a spaceship during a flare, although perhaps still undesirably large, does not differ greatly in its biological effect from doses received on earth from natural and man-made sources. Although some biological and dosimetry experiments are needed to evaluate flare radiation hazards, the control of the dose received during a flare can perhaps be relegated to the status of an engineering problem or of a statistical prediction problem. Hence, one sees that in planning ahead for space flight it will perhaps be necessary to provide a small heavily shielded region in the space craft. One would hope that occupancy of this cramped shielded space might be for only a very small part of the time. When the space traveler is not huddled inside this flare shield he presumably will be in a thin pressure tank whose walls will be lined with 5 to 20 g/cm^2 of hardware, which, although it offers good protection from solar flares, offers little protection against penetrating primary cosmic radiation.

An important problem is the determination of the relative biological effectiveness of the heavy fragments present in cosmic rays. Much physical and biological work has been done on heavy ions by many investigators. The high charges present on the heavy ions produce intensely ionizing tracks in materials that they strike. There is a question whether a single such dense particle track can cause a gross biological effect, as for example in the brain. It is not the purpose of this article to discuss this latter point in any detail from the biologic point of view, but rather to gather together some of the large amount of published material now available on the subject of heavy ions. Heavy ions are still to some extent an unknown in the astronaut radiation problem, and adequate earth or satellite experimental facilities are not now available to assess their seriousness.

The first indication that ions heavier than protons are present in the primary cosmic radiation was secured from observations of densely ionizing tracks in emulsions flown just below the top of the atmosphere. Since the Z of a particle can often be found by an examination of its track of developed silver grains in nuclear emulsions, it was soon realized that carbon, nitrogen and oxygen, as well as ions as heavy as iron, were present in decreasing numbers with increasing Z. The number of lithium, beryllium, and boron ions is rather small, as indicated in Tables 5, 6, and 7, but nevertheless these ions are present. The changes in the intensity of the heavy ions with the latitude at which they are measured, caused by the earth's magnetic field, allows their energy spectrum to be ascertained in a manner analogous to that used to secure the spectrum of the primary protons. The use of the earth's magnetic field as a large spectrometer yields the results shown in Figure 1. The equations for these spectra are given in Table 8.

In evaluating the behavior of heavy ions in a stopping medium it is important to know their charge state as a function of position along their path. The charge state usually is not single-valued, nor is it equal to Z, but it has some intermediate value between zero and Z. The charge state changes with velocity for a particular ion, but the change in charge state with different stopping media for a given velocity and density is quite small. The equilibrium charge state should be thought of as the result of a competition between the loss of electrons to and the capture of electrons from the medium. The charge of any one ion fluctuates along

Table 5

COMPOSITION OF GALACTIC COSMIC RAYS RELATIVE TO THE COMPOSITION OF THE UNIVERSE NORMALIZED TO HYDROGEN

Element	Cosmic rays	Universe
H	100	100
He	16	8
Li, Be, B	0.24	$\approx 10^{-6}$ (light component)
C, N, O, F	1.2	0.2 (medium component)
$Z > 10$	0.4	0.3 (heavy component)
Fe group	0.1	0.003
$Z > 26$	$\sim 10^{-4}$	10^{-6} (very heavy component)

Table 6

ABUNDANCE OF CONSTITUENTS OF THE HEAVY-ION COMPONENT OF GALACTIC COSMIC RAYS

Element	Abundance (%)
Li	3.9
Be	1.7
B	11.6
C	26.0
N	12.4
O	17.9
F	2.6
$Z > 10$	23.9
	100.0

Table 7

ABSOLUTE FLUXES OF GALACTIC COSMIC RAY PARTICLES

Element	No./m.^{2}sec.ster
H	610 ± 30
He	88 ± 2
Li, Be, B	1.6 ± 0.4 (light component)
C, N, O, F	5.7 ± 0.28 (medium component)
$Z > 10$	1.94 ± 0.25 (heavy component)

Table 8

ENERGY SPECTRA OF PRIMARY COSMIC RAYS*

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

*After Peters, ref. 1.

its path and eventually declines to zero at the end of the path.

There is at present no rigorous theory relating the velocity and charge state for a given ion in a given medium. An excellent review of the theoretical situation has been given by Neufeld.[6] Bohr suggested that an ion of large Z will lose all its electrons that have orbital velocities less than its translational velocity through the stopping medium. This is certainly qualitatively true. Bohr argued that the slower and less firmly bound electrons are the most easily removed, and that in the inverse process those electrons are most likely to be captured in an orbit whose characteristic velocity is close to that of the ion moving through the medium. Lamb, on the other hand, stated the stripping conditions in another way, that the moving ion is stripped of its outermost electrons until the ionization potential of the next stage of ionization is greater than the kinetic energy of an electron having the velocity of translation of the ions through the medium. At best, the experimentally measured values for the ionic charges as a function of the velocity agree only roughly with those predicted from either of these theories. Furthermore, the theory of the stopping medium and its density has not been considered at all. There are experimental data to show that fission fragments have a higher ionization in argon than in helium, an effect that is not found with either oxygen or neon ions passing through hydrogen, helium, nitrogen, or argon. It is possible that the effect is too small with oxygen or neon but is large enough to observe with fission fragments.

The average charge of an ion increases with the pressure of a stopping gas up to a plateau value. This effect depends on the relative length of the average time between successive charge-exchange collisions compared with the average time for radiation de-excitation of the ion from its excited state. If the collisions are infrequent, electrons that have been excited but not separated completely from their ions can radiate energy and drop back to their original state. If the collisions are closer together in time than the de-excitation processes, the orbital electrons are successively excited to orbits of higher and higher energy and are eventually removed from the ion. In an ion that is in equilibrium with its stripping medium, having been several times ionized and yet retaining several electrons, these remaining electrons are not in their ground state but are in a continual state of excitation. One of the difficulties encountered in heavy-ion theory is that the ions are actually in an excited state whenever moving inside a medium. So far all the theories have been for ground-state ions.

It would be desirable, in order to use the Bohr or Lamb theories in a solid or liquid, to know the distribution of electron orbital velocities or energies for an ion that is continually perturbed by collisions with a relatively high frequency. Neufeld does consider the effect of the moving ion on the medium and the back-reaction of the rearrangement of the electrons in the medium on the electrons of the ion.[6] This refinement has the advantage of being applicable to any ion, but the Bohr theory is applicable only to ions near the upper end of the periodic chart.

Many experiments have been conducted to measure the ranges of heavy ions of different energies in a variety of materials. There are data for range vs energy, as well as stopping power as a function of range. This material has been brought together in one reference.[7]

At present, experimental work to evaluate the biological and physical problems that arise in connection with heavy ions is being carried out at the three heavy-ion accelerators, at Yale and at Berkeley in the United States, and at Kharkov in the USSR. In addition, work is being carried on under much more difficult conditions in balloons, rockets, and projected satellites. Unfortunately the heavy-ion accelerators available at present are capable of imparting only about 10 Mev/nucleon to their heavy ions. This is a very modest energy when compared with the energy of heavy cosmic ray primary ions. Only a very limited range of biological samples can be irradiated with these low-energy ions, because the ranges of all HLAC ions in tissue are less than 1 mm. Enzymes, bacteriophage, bacteria and yeast cells have been studied and described by several authors.[8-16]

The very low intensity of primary cosmic ray heavy ions makes it unusually difficult to assess their possible danger in space travel. It is conceivable that a few heavy ions producing rather large ionization tracks in sensitive regions of the brain might seriously impair the performance of an astronaut. This is a debatable point unsubstantiated by any neurological experiments available at present. In view of the serious implications it raises, this possibility should be further investigated.

It is known experimentally that there is a sensitive reaction of hair color, at least in certain strains of black mice, whereby a single heavy ion may bring about the cessation of color-pigment production in several adjacent hair follicles leaving a small streak and producing an effect which has been referred to as a "mouse cloud chamber." This extensive work by Chase is described by Simons.[5] It seems that this particular reaction is an unusually sensitive one, and it is not likely to be repeated with equal sensitivity in other heavy-ion interactions. Experiments closer to the problem of space flights have been reviewed by Simons,[5] who limited his considerations to those experiments which bear on the immediate medical problem of heavy-ion damage. Figure 6, based on Simons' data, shows the number of ion pairs formed per micron of path in water, an approximately tissue-equivalent material, plotted against the range of these particles in water. Carbon, neon and iron are represented in separate curves. The iso-energy curves are also shown in this figure, which contains a condensation of most of the important information available on the interaction of heavy ions with tissue, except for the radial variation of track ionization. The variation of the energy of the particles in the region of the earth during a sunspot cycle is indicated. Except for a few earth radii the earth's magnetic field becomes quite small and the magnetic cutoff is absent, allowing penetration by particles down to energies that can pass through the much weaker solar magnetic field. The regions in which tracks terminate by thin-down rather than by nuclear collisions is indicated; this distinction probably has considerable biological significance. The region of cosmic ray hits as defined by Schaefer is shown.[17] The three regions differing in the qualitative appearance of their radial distribution of ionization are roughly shown. Finally, the region presently covered by accelerators and the region that could possibly be covered by projected accelerators are indicated. Figure 7 shows particle energies plotted as a function of their velocities.

Unfortunately no experiments performed thus far in balloons or rockets have been arranged to resolve the three types of radiation pattern indicated in Figure 6. It is clear that this question can be resolved only by an accelerator with energies up to about 500 Mev/nucleon. Such an accelerator would make it possible for all three of the different δ-ray pattern regions to be investigated. It seems that

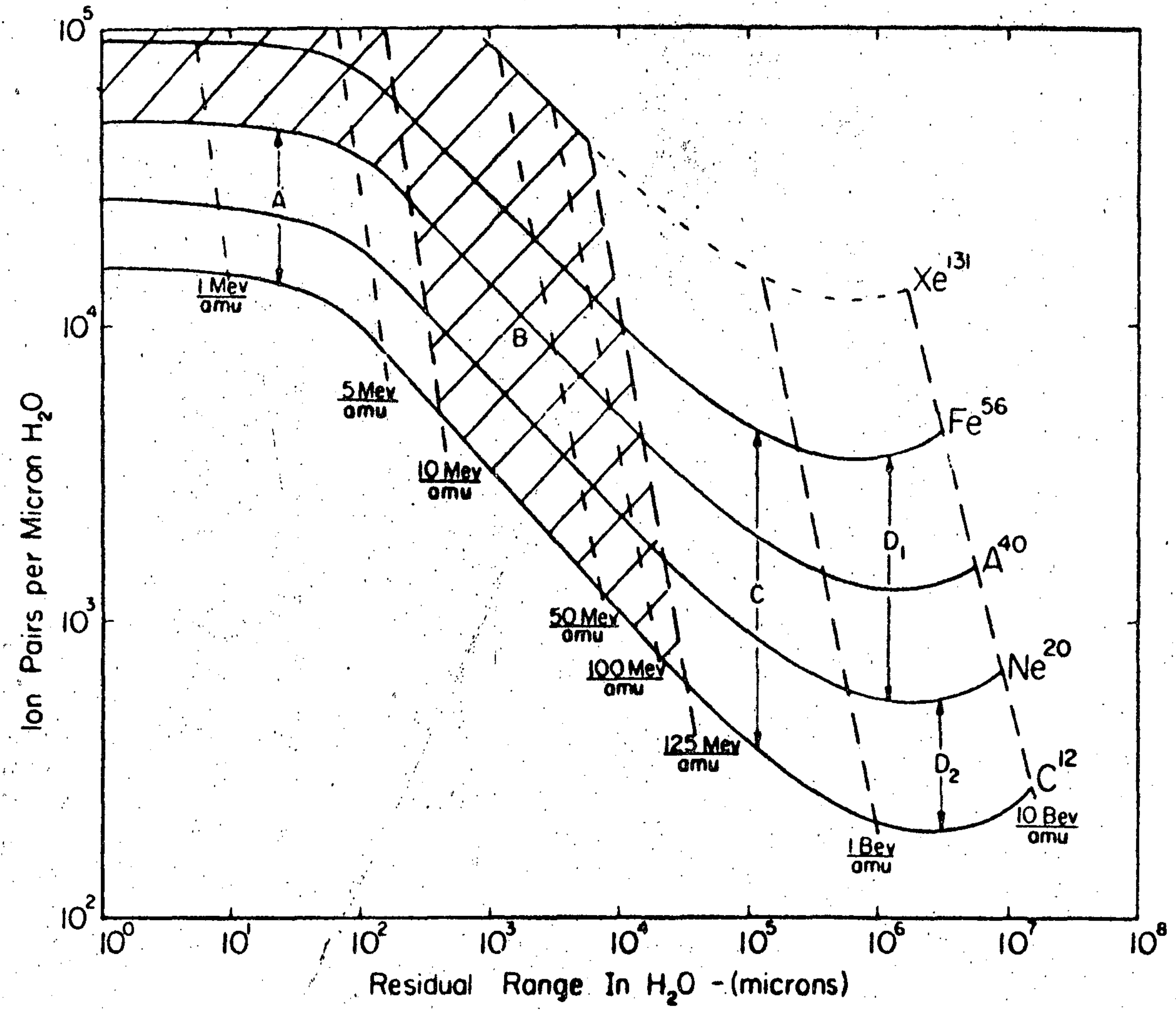

Figure 6. Specific ionization of heavy ions as a function of residual range in water. Adapted from Simons (1960). Regions:

A. HLAC operating conditions (1 to 40 amu; up to 10 Mev/amu). Tracks have densely ionizing cores and limited radial δ rays, ending by thin-down tracks.

B. Additional region included by projected future accelerators (1 to 131 amu; to about 125 Mev/amu).

C. Minimum energy of particles that can penetrate to the top of the atmosphere at middle latitudes varies within this region, from 125 Mev/amu at sunspot minima to 1 Bev/amu at sunspot maxima. Tracks have densely ionizing cores and extensive radial δ-ray patterns, and may have either thin-down or collision endings. The smaller particles in this region have somewhat less densely ionized track cores than the heavier particles.

D_1. 1 to 10 Bev/amu; 20 to 56 amu. Tracks of particles in this region have densely ionizing cores and extensive radial δ-ray patterns, and end by collisions.

D_2. 1 to 10 Bev/amu; 12 to 20 amu. Tracks of particles in this region have extensive radial δ rays and less densely ionizing cores, and end by collisions. From Wallace (ref. 7).

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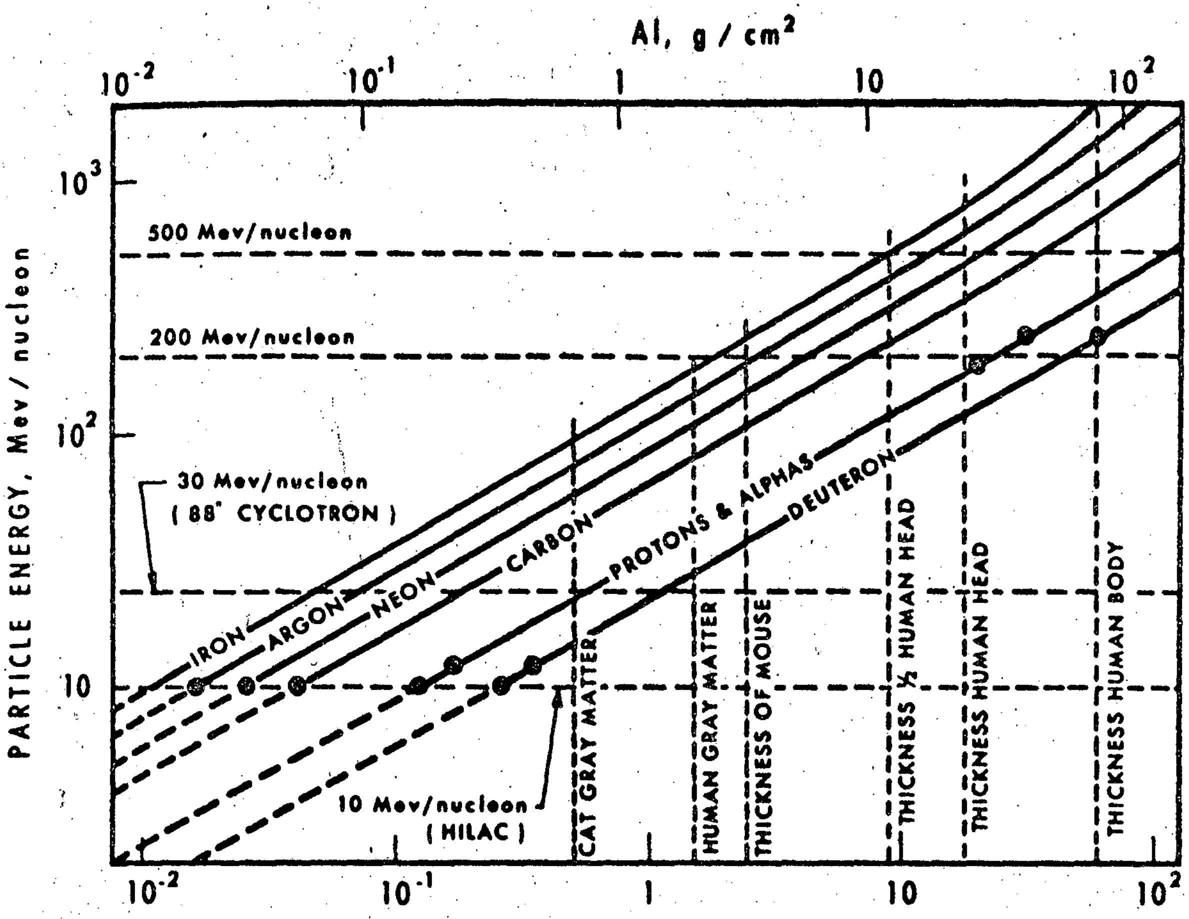

Figure 7. Particle energy vs. range in aluminum for several ions from deuterium to iron. Important biological thicknesses are shown as well as the energy presently available in two accelerators. The 200 and 500 Mev/nucleon levels are for proposed medical accelerators.

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going to energies higher than 500 Mev/nucleon would be of less interest, because the heavy-ion track patterns give way to collisions producing stars which may not be very different from those provided by proton accelerators presently available. Stars made in tissue by ion-nucleus collisions would have more prongs than those made by protons, but this may have only modest biologic implications.

The incident intensity of the heavy ion is such that at altitudes above 100,000 feet there is about 1 dense thin-down track per cm^3 of tissue per 24 hours. This rate is just sufficient so that the experiments that are quite sensitive to heavy ions, such as the "mouse cloud chamber" work of Chase, are barely possible. During a total of 4525 mouse hours above 90,000 feet, five gray streaks were observed, giving one identifiable gray streak per 38 mouse days. The streaks are interpreted as being caused by heavy-ion damage to the mouse hair follicles by a particle traveling roughly parallel to the skin. Mouse hair follicles are separated by about 100 microns. If the radial extent of a heavy primary track is of the order of only 10 microns it would seem that more experimental work is called for to resolve this apparently greater effective radial range than would be expected. It seems inescapable that the spots and streaks of gray hair are due to single ionization events. There is some evidence that the effect of these single ionization particles is transmitted to the affected follicles by their supporting cells.

It can be concluded at present that the physical understanding of heavy-ion behavior in matter is on a fair basis and that the technology for producing and accelerating heavy-ions to several hundred Mev is well developed. Although the maximum energy now available from accelerators is disappointingly only 10 Mev/nucleon, the biological experiments that have been performed with them indicate that heavy ions produce quite different effects from those of X rays: for example, there is evidence for single-hit large effects in addition to the mouse hair-graying reactions. The possibility that variables not now available such as a variable radial charge distribution may become available in bioradiology experiments with heavy ions is of some interest.

VAN ALLEN RADIATION BELT

In order to make this discussion reasonably complete, something must be said about the Van Allen radiation belt. Such a large number of measurements have been made and an even larger number of papers written on this subject, that it does not seem to be worth-while to go into it at length. Briefly, the Van Allen radiation belts are localized with regard to space travel on a lunar or planetary scale and would be traversed very quickly. There seems to be no advantage to orbiting satellites with human occupants at the particular altitude covered by these radiation belts. If a satellite did orbit for some time in one of the Van Allen radiation belts, the accumulated dose would of course be fairly high.

For a belt traversal of a few hours at the velocities appropriate to a lunar mission, it seems reasonable to expect a dose of about 5 r to be received during one pass. This is such a small amount of radiation that it seems relatively unimportant to make shielding preparations specifically for it. The only serious radiation problem in connection with the Van Allen belt might arise if the vehicle on its return from a lunar or planetary mission were to establish itself in geocentric orbit that through error passed through the Van Allen belt many times before finally landing.

Under these circumstances the Van Allen radiation might prove serious; however, the 5 to 20 g/cm^2 that seems to represent the average inherent shielding value of a functioning space capsule would certainly go a long way toward eliminating this radiation problem.

ADDITIONAL RADIATION SOURCES

There are some other possible sources of radiation encountered in space travel. Probably the principal one is the reactor that might be carried in a vehicle either for propulsion or as an electrical power supply. It seems unnecessary to discuss the radiation shielding and reactors in this report, because a vast amount of data has been accumulated on this subject in connection with the aircraft nuclear propulsion program. It is not easy to carry the required shielding and to have a reactor of adequate power. Fortunately it is fairly easy when in space to take advantage of the inverse-square law. Serious reactor radiation problems still remain during landing or take off of such a vehicle.

The last possible source of radiation which we have not discussed would be the surface of the moon or of a planet such as Mars or Venus if it had an inherently highly radioactive surface. This certainly seems unlikely. At present there is some evidence that the radiation emanating from the surface of the moon is either quite small or negligible. It is reported that the Soviet rocket that struck the moon in September 1959 did not record either a rise or fall in its radiation counting rate as it approached the lunar surface. If the moon were completely devoid of radioactivity one should have expected a drop by a factor of 2 as the surface was approached. Such a drop was not observed, perhaps indicating that there is a modest amount of radioactivity roughly equal to half the cosmic ray rate. Certainly this is not a serious amount.

It would seem unlikely that the surface of the moon or of a planet would contain large quantities of radioactive material that would produce important biological effects. It seems much more likely that the distribution of natural radioactive materials is more locally concentrated than on the earth. There are a few specialized regions on the earth, for example in uranium mines, where dose rates are rather high compared with the permissible occupational level, but these regions are so restricted that they certainly do not in any way limit our activity; the same situation probably prevails on other planets because there is no particularly obvious reason why radioactive materials should be concentrated by any known geologic process. The tendency seems rather to be toward dispersion, and it is our experience that radium is one of the most widely distributed elements on earth. This observation indicates that surface radiation is not likely to limit space operation.

CONCLUSION

In summary it can be said that solar-flare protons are the only radiation problem that seems to offer potential hazards for space travel in any way commensurate with those inherent in the travel itself due to propulsion and guidance problems. These protons have been discussed in fair detail, and it is seen that their incidence and intensities are such that the hazard they probably present is not nearly as great as other hazards inevitable in such travel; however, they do offer a hazard of sufficient potential to warrent extensive study of their properties, and an effort should be made to provide predictions of their incidence. It would seem that the occurrence of serious flares is sufficiently rare so that large, comfortable, shielded regions in space vehicles are not called for, but it might be desirable for missions lasting several months or years to provide cramped and perhaps completely inoperative locations (for example, inside a fuel tank) where the crew could hide for a few hours once a year. The radiation problem in space, although well worthy of further study, should certainly not be a limitation to the overall possibility of space travel.

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