Radiation Hazard in Space from Solar Particles

Abstract. *There were about six solar flare events during the last solar cycle which would have exposed a space traveler to serious radiation from solar particles. The radiation from two of these events was intense enough to necessitate extra precautions being taken to protect space travelers.*

The radiation hazard that space travelers will encounter is threefold: (i) the radiation due to particles emitted by the sun in solar flares, (ii) the intense radiation in the Van Allen belts surrounding the earth, and (iii) the radiation caused by galactic cosmic rays which, although much less intense than the other two, is difficult to reduce by shielding. Galactic cosmic radiation has been recognized since 1912 but the other two sources of radiation have been only recently discovered. Van Allen first detected particles trapped in the magnetic field of the earth in 1958 and since then this radiation has been widely investigated (*1*).

Solar particles were first detected at the surface of the earth in 1942, but during the next 14 years only four such cosmic-ray increases were detected at ground level by the ionization-type detectors then being used. On 23 February 1956 there occurred a great increase of cosmic rays which was well documented by many detectors both at ground level and in balloons. During the International Geophysical Year, as detection methods became more sensitive, as many as 10 to 15 such particle-producing flares a year were observed. Now that satellite-borne instruments have increased the sensitivity of the measurements, even more particle-producing flares are recognized which could not have been observed by earlier detection methods.

The emission by the sun of particles with energies from a few million to a few billion electron volts occurs in solar flares. We now know that many flares emit the lower energy particles, but that the higher energy particles are only rarely emitted, or at least only rarely detected at the earth. One of the most ingenious techniques used to detect the solar particles is cosmic noise absorption. Special wide-angle receivers (30 Mcy/sec), called riometers, continually monitor the radio noise from the galaxy. The absorption of this radio signal is increased when the ionization in the atmosphere at heights of 30 to 100 km is increased. At high geomagnetic latitudes, cosmic noise absorption is used as an indicator of the arrival of solar paricles that stop high in the atmosphere, increasing the ionization there. Until recently there was no satisfactory quantitative relationship between the energy spectrum of the solar particles and the cosmic noise absorption; nevertheless, riometers have provided an extremely useful ground-level monitor of solar cosmic rays. With recent advances in our knowledge of the solar-particle spectrum (*2*) the riometer response has been put on a more quantitative basis.

The radiation from protons and electrons trapped in the magnetic field of the earth can be avoided by a departure from the earth at either pole. A trajectory which would traverse the Van Allen belts quickly, thus keeping the radiation dose low, could also be used. Many measurements and calculations have been made because of this problem, and it is generally agreed that space travelers will be able to leave the earth without suffering excess radiation. The dose rate under 1 g/cm² shielding (~ 0.13 cm of steel) in the Van Allen belts is about 20 rad/hr, with considerable spatial and time variations in this rate. For orbiting missions, the radiation of the Van Allen belts must be considered in the choice of orbital parameters for instrumental as well as manned flights.

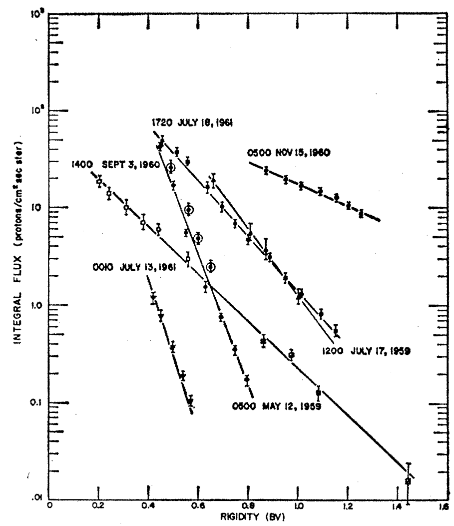

Fig. 1. Integral proton spectra are shown as exponentials in rigidity at selected times for six different solar flares. Data points taken from counter ascents are shown as solid symbols; those taken with emulsions, as open symbols.

The galactic cosmic rays should not present a serious hazard; yearly doses in space will vary from 5 to 15 rads. No reasonable amount of shielding will reduce this dose significantly since secondary particles generated in the shield may contribute even more radiation

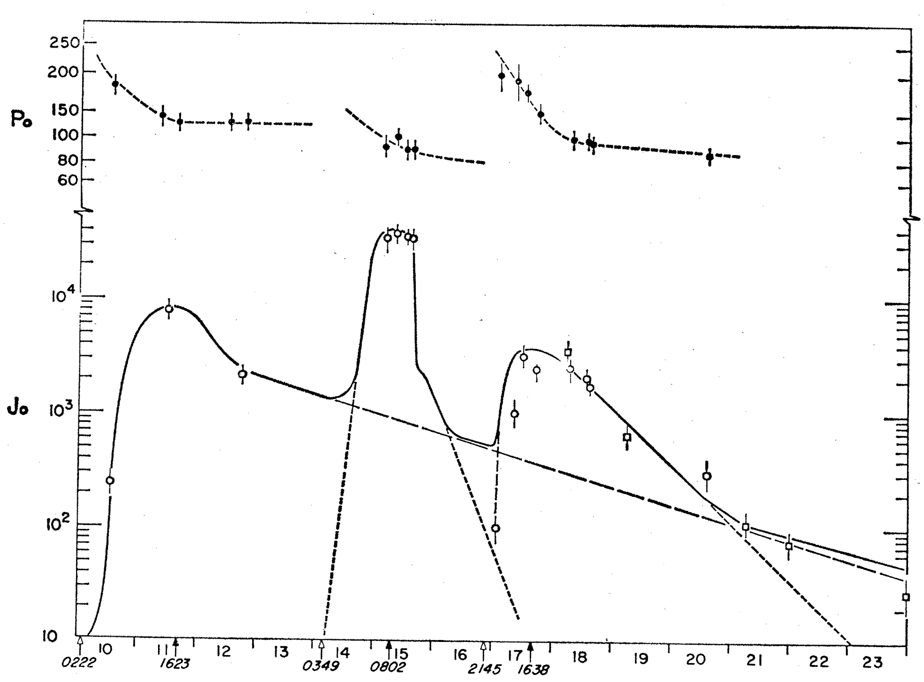

Fig. 2. The time variations of P_0 (Mev) and J_0 (protons/cm² sec ster) is shown for the 10, 14, and 16 July 1959 flares. The measured values of P_0 are shown connected with a continuous curve. The plotted values of J_0 are determined from P_0 and the measured particle flux; the continuous curve of J_0 is from riometer data and the P_0 curve. The times of the flare and sudden commencements of magnetic storms are indicated.

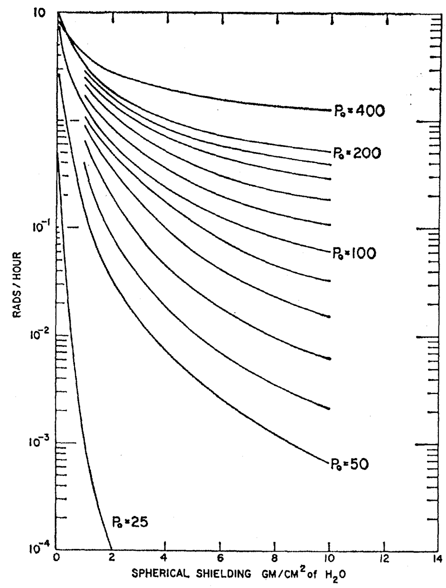

Fig. 3. Radiation dosage as a function of shielding thickness for a solar flux of 10^3 exp $-P/P_0$ protons/cm^2 sec ster with various values of P_0.

than the primary particles. The shielding (1000 g/cm^2) provided by our atmosphere reduces this dose to about 0.03 rad per year. The galactic radiation shows a negative correlation with solar activity—thus years of maximum solar activity will have the lowest galactic cosmic-ray flux.

The solar-flare particles will contribute the most uncertain and potentially the most dangerous part of the radiation dosage received by a space traveler. We have calculated the amount of radiation received at earth from the largest solar flares of the last 5 years

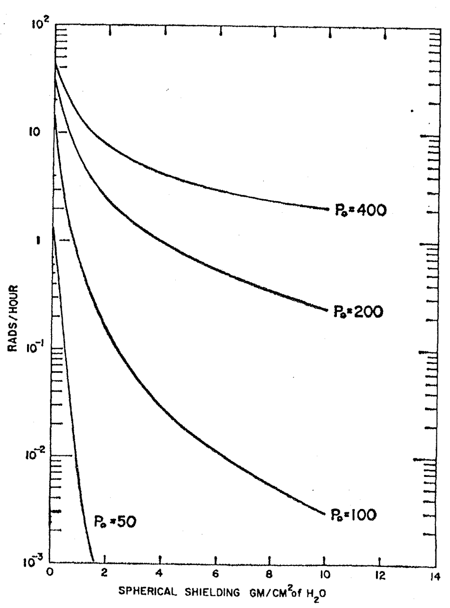

Fig. 4. Radiation dosage as a function of shielding thickness for a solar flux of 10^3 exp $-P/P_0$ α-particles/cm^2 sec ster with various values of P_0.

and have expressed radiation in units of rads (1 rad = 100 erg/g). We neglect secondary particles resulting from interactions of the solar protons in the shielding material and calculate the radiation, assuming each proton loses its energy only by ionization. If the exponential spectrum which we shall show best fits the solar particles is used, the neglect of secondary particles causes less than 10 percent error in the total radiation dosage.

For the most part, solar-flare particles arrive almost isotropically at the earth for several days after the visible flare has occurred on the sun. The particle intensity at first increases for about a day and then decreases and may take up to 5 days to decrease to the pre-flare intensity. The energy spectrum of the particles changes in time, with high energy particles reaching their maximum intensity before the lower energy particles. Since each of the techniques used for detecting these particles has been definitive over only a part of the energy spectrum, it has been difficult, first of all, to relate the various measurements, and secondly, to obtain a simple and useful representation of the number spectrum of the flare particles and its development with time. It has been customary to express the differential-number spectrum of the incident particles as a power law in energy

$$\frac{dJ}{dE} = \frac{K}{E^n}$$

where dJ/dE is the differential number of particles with energy, E. When this representation has been used, K and n are functions of both energy and time; n has been found to increase with increasing energy, and usually to increase with time after the onset of a solar event.

The power law representation of the energy spectrum has not been satisfactory in describing the energy distribution of the solar particles. Its extrapolation to lower energies has resulted in widely differing estimates of the particle intensities at low energies, thus calculations of the radiation dosage space travelers will receive from these solar particles have varied by more than factors of 10 (*3, 4*). This factor of uncertainty could mean the difference between life or death for a space traveler. The difference in shielding requirements imposed by the varying estimates is great and the minimum shielding requirement has been generally accepted to be about 10 g/cm^2. Satellite-borne detectors can now measure directly the radiation hazard in space; however, there will not be many large flares from which to collect new data until 1969, the next period of maximum solar activity. Thus, it is most important to obtain a reliable estimate of the radiation in space from the data already collected from various detectors operating during the last period of high solar activity (1958–1960).

After careful examination of the data collected by the various detectors that have been recording solar-flare particles, Freier and Webber (*2*) recently found that a two-parameter system best defines the spectrum of solar particles. They have shown that the spectra of solar particles fit an exponential of the form:

$$\frac{dJ}{dP} = \left(\frac{dJ}{dP}\right)_0 \exp\,(-P/P_0)$$

The parameter P is the momentum per unit charge of the particle, or the magnetic rigidity. (The magnetic rigidity is the product of the magnetic field and the radius of curvature of the particle in that field.) The quantity dJ/dP is the differential intensity of solar particles with rigidity P. The constants $(dJ/dP)_0$ and P_0 are functions of time *only*. With this spectral notation it is simple to write the integral equation from the differential spectrum

$$J = J_0 \exp - P/P_0$$

where J is the integral flux of particles having rigidity $\geq P$. The constants in the two equations are related by

$$\left(\frac{dJ}{dP}\right)_0 = \frac{J_0}{P_0}$$

This relationship between the differential and the integral intensity of solar particles is used when comparing data from an integrating detector such as a geiger counter and a differential detector such as an emulsion. The integral spectra of protons measured at selected times during six different flares is shown in Fig. 1. It is apparent that exponential-rigidity spectra represent the data over a wide range from 0.2 to 1.4 Bev rigidity (an energy range of 20 to 800 Mev for protons).

Such spectra apply for proton energies greater than about 20 Mev providing that the time after the flare onset is a few times the normal travel time for the particles from the sun, so the particles have had time to reach the earth. With the exponential-rigidity spectrum, solar protons, α-particles, and heavier nuclei have the same spectral representation with the same P_0. The constant, J_0, is in general different for protons, α-particles, and heavier nuclei.

There appears to be a significant difference in the composition of solar cosmic rays and galactic cosmic rays. From seven of the ten flares in which it has been possible to measure solar α-particles, it has been found that above a certain rigidity (or momentum per unit charge) α-particles and protons are about equal in abundance. However, in some flares the protons have been found to be more than 40 times as abundant as the α-particles. In galactic cosmic rays the protons are about 6.5 times as abundant as α-particles of the same rigidity. The ratio of α-particles to heavier nuclei is about 100 for solar cosmic rays and about 10 for galactic cosmic rays.

The constants P_0 and J_0 vary from event to event but their time behavior for different events is similar. We have studied in detail the 16 largest events occurring during the past 4 years. From the data obtained with balloon-borne detectors flown by the cosmic ray group at the University of Minnesota, as well as from all other existing data, the time behavior of the constants has been determined for 11 flares. The quantity P_0 always decreases with increasing time; J_0 increases with time for about the first day after the flare, usually reaching its maximum value about the time the magnetic storm caused by the flare reaches the earth. Then J_0 decreases with time; sometimes the flare particles are still detectable a week after the flare, although the more usual duration is 2 to 3 days. In Fig. 2, we show the time behavior of J_0 and P_0 for the three flares of July 1959.

The exponential-rigidity representation of the spectra of solar particles has been shown to fit flux measurements for energies greater than about 20 mev. At lower energies where data have been obtained in rockets and satellites (*5, 6*) for the flares of November 1960, and in satellites (*7, 8*) for the flares of July 1961 and 28 September 1961, the particle fluxes for protons less than 20 Mev do not fit the same exponential as do the higher energy particles, but the flux of low energy particles is in excess of that predicted by the exponential spectrum. This excess occurs only at certain times and is closely related to the arrival of the associated magnetic storms. Further experiments should clarify the relationship between the high energy "cosmic-ray" particles and these low energy "magnetic-storm" particles.

We have calculated the radiation dosage (*RD*, in Mev/cm² sec) under spherical shielding of H_2O of various thickness according to the formula:

$$RD = \int_0^E \int_0^\Omega \left(\frac{dJ}{dE}\right)\left(\frac{dE}{dx}\right) dE\rho \, d\Omega$$

where ρ is the density of the shielding material. We shall assume all paths normal to the surface of the sphere and the isotrophy of protons, so $\Omega = 4\pi$. We have expressed the differential flux in terms of rigidity and numerically integrated over the rigidity. The dE/dx

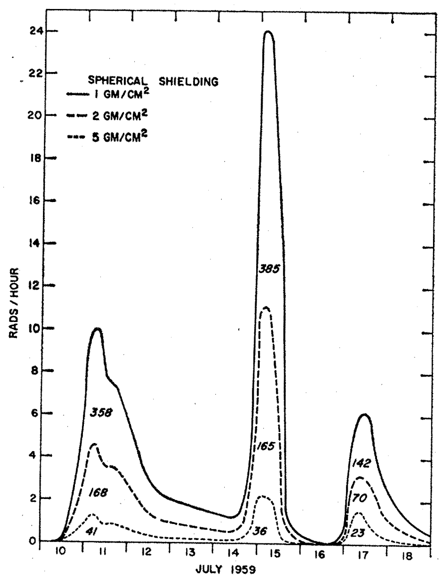

Fig. 5. Radiation dosage from solar protons as a function of time for the 10, 14, and 16 July 1959 flares under three thicknesses of spherical shielding. The numbers show the integrated dose received from each flare.

values for protons in H_2O given by Rich and Madey (*9*) were used. The results of the numerical integration are given in Fig. 3 where the radiation received from a flux of $10^3 \exp - P/P_0$ protons per cm² sec⁻¹ ster⁻¹ is plotted as a function of shielding thickness for various P_0. Figure 4 shows the same result for α-particles.

The time variation of radiation dosage under shielding thickness of 1, 2, 5, and 10 g/cm² has been calculated for some of the large flares of the last 4 years. Figure 5 shows the radiation which would have been received from solar protons between 10 and 19 July 1959 from the three large flares which occurred on 10, 14, and 16 July. The integrated doses received under spherical H_2O shielding of 1, 2, 5, and 10 g/cm² are tabulated (Table 1) for this series of events as well as the other major events occurring during the last sunspot cycle. In events where the low energy "magnetic-storm" particles have been measured we have calculated the additional dose to be expected from these particles. We have calculated the doses for the measured solar proton spectra and for α-particle spectra assuming a constant ratio above a fixed rigidity for the proton to α-particle abundance. We have used the measured ratio where it exists and otherwise have assumed J_0 (protons)/J_0 α-particles = 1, which is the highest α-particle abundance observed. We denote this ratio as p/α in Table 1. This gives

Table 1. Radiation dose from solar particles under various thicknesses of spherical shielding (H_2O). Doses are given in rads.

Protons				p/α	α-particles			
1 g/cm²	2 g/cm²	5 g/cm²	10 g/cm²		1 g/cm²	2 g/cm²	5 g/cm²	10 g/cm²
				23 February 1956				
55	35	20	14	1	140	80	35	17
				10 May 1959				
315	116	27	5	1	105	18	2.4	0.2
				10 July 1959				
360	170	40	14	1	150	30	5	1.0
				14 July 1959				
385	165	35	8	1	180	25	3	0.5
				16 July 1959				
140	70	25	9	1	100	30	6	1.6
				3 September 1960				
5.5	3.1	1.2	0.7	30	0	0	0	0
				12 November 1960				
*216	119	45	24	1	274	110	31	11.7
†490	115	20	4		32	5		
				15 November 1960				
*180	92	27	12.8	2	71	25	6.1	2.5
†117	22	3	0.4		6.5	.4		
				12 July 1961				
40	15	2	0.3	1	3	0.4	0	0
				18 July 1961				
50	27	9	4.1	6	8	3	0.6	0.2

* High energy. † Low energy.

the maximum possible radiation dose due to solar α-particles.

These represent the doses experienced on the surface of a man who is inside a spacecraft of designated thickness. We believe the fluxes on which these doses are based are correct to within a factor of 2 for shielding of 1 g/cm^2 for the first five events in Table 1. For the other events at 1 g/cm^2 and for all events at the other thickness this flux is believed to be accurate to $\pm$ 25 percent.

In the absence of any shielding considerations we shall assume that the typical spacecraft or satellite-observing station will have a wall thickness approaching 2 g/cm^2. Under these conditions a number of events over the last solar cycle would have provided integrated particle doses in excess of 200 rads. During the period from 10 to 20 July 1959 the total dose was 490 rads and from 12 to 18 November 1960 the total was 488 rads. The flares on 23 February 1956, 26 March 1958, 7 July 1958, and 10 May 1959 all produced doses greater than 100 rads inside a spacecraft with shielding of 2 g/cm^2.

The assessment of the damage caused by these doses is a difficult and, as yet, unsolved problem. First of all, the damage depends upon the exposure of certain critical areas of the body such as the eyes, brain, liver, and so forth, to the radiation. It may be possible for the pilots to assume positions or take up locations which would greatly reduce the dose to critical areas. Secondly, it is very difficult to evaluate the effectiveness of the heavily ionizing particles, especially in the killing of individual cells.

It seems reasonable to assume, however, that any event producing more than 100 rads in a period of 1 week is capable of causing enough damage at least to reduce the efficiency of a man appreciably if no extra precautions are taken. The larger doses may render him completely inoperative and cause failure of the mission. An increase of wall thickness in spacecraft to 5 g/cm^2 (10 lb/ft^2) would reduce the dose in the most extreme event to less than 135 rads.

The extent of the hazard of these solar cosmic-ray outbursts depends essentially on encountering one of the large events. As we have seen, there are six to eight events which occurred during the last solar cycle that could possibly present a serious problem in space in terms of immediate damage to a man. The cumulative effects of smaller events considerably exceeds accepted tolerance doses, but should not result in the failure of a specific mission. Of the major solar events, one occurred in 1956, two in 1958, two in 1959, and one in 1960; that is within 3 years of the peak of the sunspot cycle occurring in 1958. Evidence from periods near the last two sunspot minimums and the one we are entering now indicate that there are periods of 3 to 4 years when no large events would be expected to occur.

For short missions of a few days or weeks, such as trips to the moon or for orbiting stations in the vicinity of the earth, we may attempt to predict the possibility of a major event by studying local conditions on the sun. If "solar weather predictions" are used it should be possible to travel at periods of sunspot maximum. At a sacrifice of approximately 50 percent of the available time, it should be possible to decrease the chance of encounter with a large event by a factor of about 10 for a predicting period of 2 weeks. This reduces to about 1 percent the probability of encounter with a large flare event for a two-week voyage.

PHYLLIS FREIER
WILLIAM R. WEBBER

School of Physics, University of Minnesota, Minneapolis

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Abscisin II, an Abscission-Accelerating Substance from Young Cotton Fruit

Abstract. *Crystalline abscisin II, with a tentative molecular formula of* $C_{15}H_{20}O_4$, *has been isolated from young cotton fruit. It accelerates abscission when applied in amounts as low as 0.01 μg per abscission zone. It inhibits indoleacetic acid-induced straight growth of* Avena *coleoptiles but has no gibberellin activity on dwarf maize.*

Endogenous abscission-accelerating substances are now known to occur widely in the higher plants (*1*). Recently, abscisin (I) was isolated from the mature fruit wall of cotton (*2*), but little is yet known of its physiological properties. The abscission-accelerating substance which is best known physiologically occurs in the young fruit of cotton; its activity reaches a peak at the time of the onset of young fruit abscission (*1*). We now report the isolation of this substance, here named abscisin II, and describe some of its chemical and physiological properties.

Abscission-accelerating activity was measured with explants (excised cotyledonary nodes) of 14-day-old cotton seedlings. Seedlings were grown at 32° ± 2°C with a 15-hour photoperiod of 22,000 lu/m^2 provided by "warm-white" fluorescent lamps. The explants consisted of 3-mm stumps of the cotyledonary petioles and of the stem, and a 10-mm stump of the hypocotyl. Explants were placed upright in stainless steel holders in petri dishes containing a 5-mm layer of 1.5-percent agar. Fractions to be tested were applied to the petiole stumps in 5-μl droplets of 1.0-percent agar. Dishes with explants were kept in the dark at 30°C. Abscission was determined by applying a force of 5 g to the end of the petiole stumps at daily or more frequent intervals.

Four- to seven-day-old fruit was quick-frozen in the field with dry ice, stored at −5°, and later lyophilized to approximately 10 percent moisture. A 78-kg sample (225 kg fresh weight) was then extracted overnight at ambient temperature of 20° to 25°C with 520 liters of 80-percent acetone. After filtering and concentrating, the remaining liquid was adjusted to pH 2.0 with dilute HCl and extracted twice with equal volumes of ethyl acetate. The ethyl acetate phase was extracted three times with 2.0 percent aqueous sodium bicarbonate. The