The Chemical Composition and Energy Content of the Energetic Cosmic Radiation*

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A brief survey is made of our present knowledge of the composition and energy spectra of the primary cosmic radiation. The total energy carried by all forms of cosmic radiation that have appreciable penetrability into matter has been evaluated. This information, when combined with a knowledge of the rate at which the different components deposit energy in traversing matter, would permit calculations of the radiation dose that would result from exposure to the primary cosmic radiation. It is concluded that overall these radiation effects are rather small but it is emphasized that local damage can be of much greater significance.

Introduction.

Any detector or object placed outside the protection of the earth's atmosphere is irradiated by cosmic electromagnetic and corpuscular radiation that can penetrate deeply into the object. The radiation effects produced by this exposure depend critically on the physical and biological conditions involved and are one of the main topics of this conference. In this paper I present some of the data concerning the nature of this cosmic radiation that is relevant to any calculations of the magnitudes of these effects. Specifically I have summarized our current knowledge of the primary cosmic radiation and have discussed some of the factors that should be of importance. In what follows I have neglected radiation of solar origin and that present in the radiation belts, since these will be discussed by other authors.

The majority of the cosmic radiation is corpuscular in nature and is consequently subject to the effects of solar and geomagnetic modulation. Geomagnetic modulation is relatively well understood in that at any point in space within the magnetosphere, the geomagnetic field simply imposes a cut-off rigidity below which particles coming from a particular direction cannot penetrate. Solar modulation has been extensively studied as a temporal phenomena and examples of the resulting variations in particle intensities are given later. However, spatial studies have been less successful and at present we do not really know either how the intensities vary throughout the solar system, nor what they are in interstellar space. Measurements of the cosmic ray gradient have been conflicting and we have to rely on theory to calculate the demodulated spectra. Fortunately these solar modulation processes mainly affect the lower energy particles and therefore it is probable that the total energy content of the cosmic radiation is not seriously influenced by these uncertainties.

In addition to the corpuscular radiation, there are also X and γ-ray components and these will not be appreciably temporally or spatially dependent unless some cosmic cataclysm occurs, such as a nearby super-novae explosion. In what follows I will first outline our current knowledge of the composition and energy spectra and then evaluate the amount of energy carried by each component. A knowledge of the incident energy, combined with a knowledge of the absorption characteristics, permit an evaluation of the gross, or average radiation effectiveness of any particular cosmic ray component. Such an averaging approach does, of course, neglect the fact that when we consider the cosmic radiation we are concerned with particles that have a spectrum of energies and a small fraction in any component will be of extremely high energy. Indeed, in fact, a single particle may have up to 10^7 ergs. These particles, or quanta, have the potential of delivering all or most of their energy into a very small volume, producing localized radiation effects of much more serious consequence than those suggested from the overall level. A similar phenomena can be produced by the highly charged particles in the cosmic radiation, which because of the Z^2 dependence of the ionization energy loss, can also deliver a large amount of energy into a very localized volume. The effects produced by these large local radiation doses on biological or solid state systems can be much more serious than would be inferred from the values for the average doses.

X and γ-Rays.

The emission of cosmic X-rays has been observed from various point sources and as a diffuse background of galactic or metagalactic origin. High energy,

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$E \geq 50$ MeV, γ-ray observations have generally shown that the energy spectra observed at X-ray energies either extrapolate sensibly or steepen at higher energies. It is thus not unreasonable to integrate the observed differential X-ray spectra to infinity to obtain an upper limit to the energy input. In all cases the energy intensities are rather small. Table I shows the values for the intensities above 10 KeV for the representative point sources Sco X-1 and Tau X-1 as well as for the isotropic background. Clearly, irrespective of how the energy is deposited the average radiation effects must be small although, once again, individual energetic gamma ray photons may produce large local effects.

Table I

(X-Ray Incident Energies)

Tau X-1 (Peterson (1970)).

$$dN = 20\ E^{-2.3}\,dE \text{ photons/cm}^2\text{.sec.keV}$$

$$I(>E) = 67E^{-0.3} \text{ keV/cm}^2\text{.sec.}$$

$$I(>10 \text{ keV}) = 4.6 \times 10^{-3} \text{ ergs/cm}^2\text{.day.}$$

Sco X-1 (Peterson (1970)).

$$I = 110\ e^{-E/4.3} \text{ keV/cm}^2\text{.sec.keV.}$$

$$I(>E) = 470\ e^{-E/4.3} \text{ keV/cm}^2\text{.sec.}$$

$$I(>10 \text{ keV}) = 6.3 \times 10^{-3} \text{ ergs/cm}^2\text{.day.}$$

Diffuse Background (Schwartz (1969)).

$$dN_1 = 10\ E^{-1.5}\ dE \text{ photons/cm}^2\text{.sec.sr.keV}$$

for $E \leq 25$ keV.

$$dN_2 = 225\ E^{-2.5}\ dE \text{ photons/cm}^2\text{.sec.sr.keV}$$

for $E > 25$ keV.

$$I(>E) = 20\ (5-E_1^{0.5}) + 450\ E_2^{-0.5} \text{ keV/cm}^2\text{.sr.sec.}$$

$$I(>10 \text{ keV}) = 1.75 \times 10^{-2} \text{ ergs/cm}^2\text{.sr.day.}$$

(A possible bump in the spectrum at 1-5 meV, Vette et al. (1970), would only raise I (>10 keV) by a few percent).

Here, as in the remainder of this paper, the energy intensities are expressed in units of ergs/cm^2.day or ergs/cm^2.sr.day. Remembering that a rad corresponds to the absorption of 100 ergs per gram of irradiated material, one could calculate the radiation effects from these energy intensities, if one knew the absorption rates as a function of energy. Of course this is a big if and represents one of the principal problems in this field.

Neutrinos.

For completeness it is appropriate to discuss neutrinos here, since they are certainly a penetrating form of cosmic radiation. Obviously their extreme penetrability implies negligible energy deposition and hence unimportant radiation effects. This is fortunate since we know very little regarding the flux of cosmic neutrinos. Burbidge (1970) has collected various estimates which suggest that probably the energy density does not greatly exceed 3 eV/cm^3,i.e. about an order of magnitude greater than that of the corpuscular cosmic radiation. (Note that for ultra relativistic particles 100 ergs/cm^2.sr. day ≈ 0.3 eV/cm^3.)

Charged Particles.

1) Electrons.

The true spectrum of the electrons in the cosmic radiation is somewhat controversial at the present time. Figure 1 shows the spectra reported in a recent paper, Marar et al. (1971), from which it can be seen that there are at least two plausible representations of the true spectrum at energies above 5 GeV, which differ in intensity by at least a factor of five. At lower energies the situation is equally complicated, although in this case the principal cause appears to be the effects of solar modulation rather than experimental inconsistencies. Figure 2 shows a schematic representation of the data available in this energy region. These results permit us to evaluate the incident energy carried by the electron component. The resulting energy intensity spectra for the various cases are shown in Figure 3.

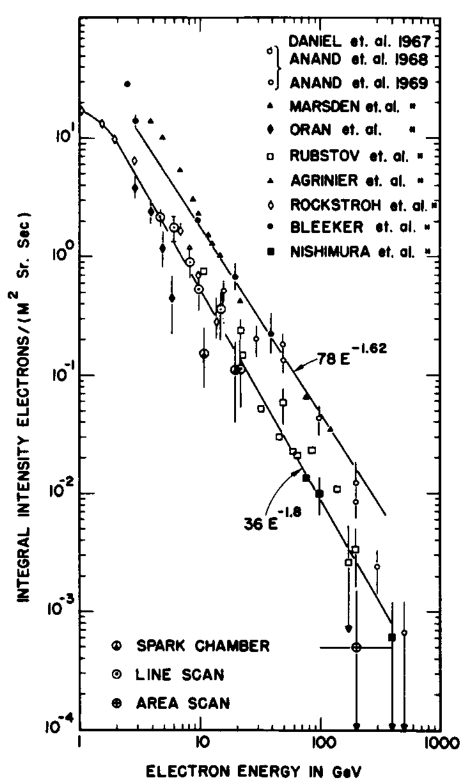

Figure 1. The integral energy spectrum of primary cosmic ray electrons above about 2 GeV, as measured by various authors. For references see the original paper by Marar et al. (1971).

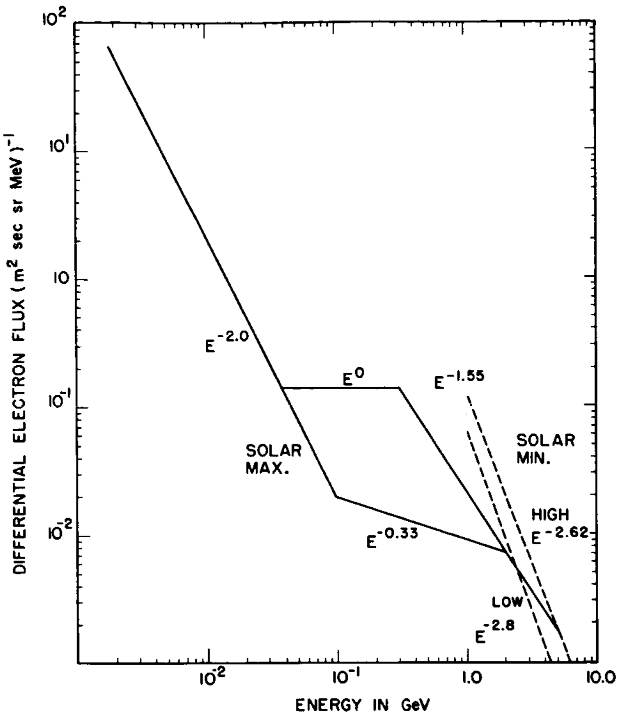

Figure 2. A schematic representation of the integral energy spectrum of low energy cosmic ray electrons as measured at times typical of minimum and maximum solar modulation.

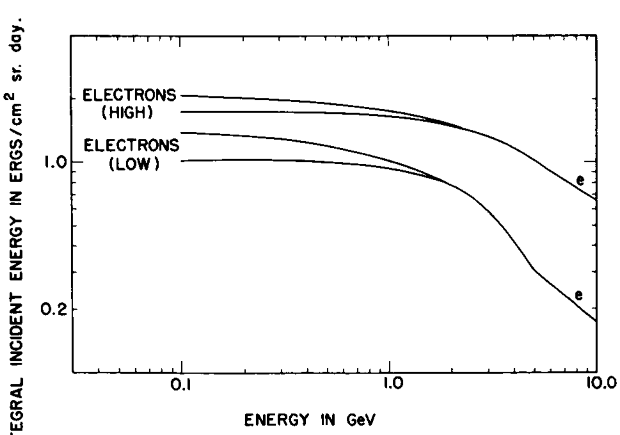

Figure 3. The integral energy intensities for cosmic ray electrons at maximum and minimum solar modulation and assuming either the high or low spectrum given in Figure 1.

2) Hydrogen and Helium Nuclei.

The energy spectra of these nuclei have been extensively studied by many workers. Figure 4 shows the differential energy spectra at times typical of solar minimum and solar maximum as recently compiled by Lezniak and Webber (1970) from selected data. At higher energies, $\geq$ 2 GeV per nucleon, the spectra of both components can be well represented as a power law in total energy with $dJ=K\ (T+m_oc^2)^{-2.5}dE$. If the kinetic energy per nucleon T, is expressed in GeV per nucleon then K=4500 for protons and 400 for α-particles. At very high energies, $\geq 10^{15}$ eV, deviations do occur from these spectra, with apparently a steepening to an exponent of about 3.0, followed at around 10^{18} eV by a flattening to the original exponent. However, the total energy carried by these energetic particles is a negligible fraction of the total.

Both components contain small fractions of isotopes other than the main one. Deuterons make up 1 or 2% of the total hydrogen component while about 10% of the helium component is probably He^3. In both cases we only know these proportions at low energies, $\leq$ 500 MeV per nucleon, but there seems little reason to expect that they would be much larger at higher energies.

3) Heavy Nuclei.

The energy spectra of the cosmic ray nuclei in the range between lithium and nickel, $3 \leq Z \leq 28$, have been studied by a large number of workers and detailed comparisons exist between these spectra and that of the helium nuclei. For example, Figure 5 is from a recent review, Waddington (1970) and shows the ratios of the helium abundance to those of various groups of heavy nuclei expressed as a function of energy. It can be seen that while there is some suggestion that at least some of these ratios are energy dependent below about 1 GeV per nucleon, it is not unreasonable to use as a working assumption the concept that all nuclei have similar energy spectra. The apparent deviations from this that are seen do not seriously affect our estimates of the total energy carried by each component. At very high energies, $\geq 10^{16}$ eV/nucleon, composition changes do occur that probably result in all the particles above $\approx 10^{18}$ eV being protons. The value assumed here for these ratios are given in Table II, together with an estimate of the mean mass number in each group. From these values we can calculate the incident energies carried by each component. As an example, the table also gives the total incident energy carried by nuclei with $T \geq 100$ MeV per nucleon.

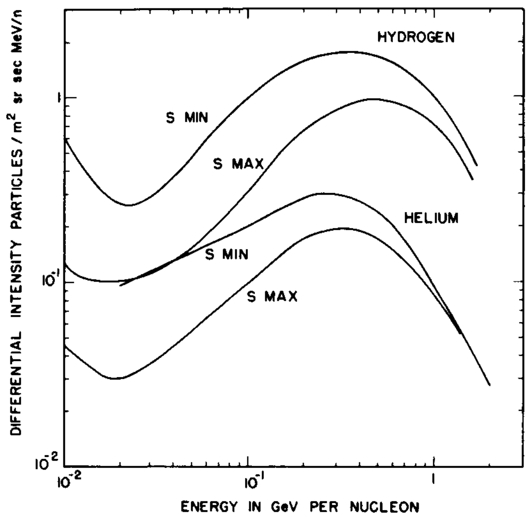

Figure 4. The differential energy spectra of hydrogen and helium nuclei below about 2 GeV per nucleon as measured by several groups. After Lezniak and Webber (1970).

that those nuclei that we believe are predominately the consequence of secondary production during interstellar propagation from the 'source' of cosmic rays to show energy dependent abundances, since we know that the nuclear parameters describing their production are energy dependent.

Energy Intensities.

The data summarized in the previous sections has been used to calculate the energy intensities, both integral and differential, carried by each major component of the cosmic radiation. The energy spectra of these intensities are shown in Figures 5 and 6. For comparison it is possibly relevant to note that the total energy intensity of cosmic ray particles at sea level and high latitudes is about 5 ergs/cm^2.sr.day, Hayakawa (1969), or 3-4% of that above the atmosphere. Although the radiation dose due to sea level cosmic rays is about 30 mrem/year, this cannot be taken as implying that the space cosmic ray dose is just 25 to 30 times greater. First of all there is the factor due to the isotropy of space cosmic rays compared to the non-isotropy of those at sea level. Secondly, and more important, is the greatly different nature of the particle

TABLE II

Charge Group		Abundance Ratio Relative to Helium	$\bar{A}$	I(>0.1 GeV/n) Ergs/cm^2.sr.day
L-nuclei	$3 \leq Z \leq 5$	1/48	9	1.53
M-nuclei	$6 \leq Z \leq 9$	1/16	14	7.07
LH-nuclei	$10 \leq Z \leq 14$	1/75	22	2.38
MH-nuclei	$15 \leq Z \leq 19$	1/600	35	0.475
VH-nuclei	$20 \leq Z \leq 30$	1/200	52	2.12
SVH-nuclei	$Z \geq 30$	1/8 x 10^5	~100	1 x 10^{-3}
		Helium Nuclei		32.5

The abundances of individual elements are still imperfectly known, with the uncertainties generally increasing at higher charges. A recent survey by Shapiro and Silberberg (1970) probably represents the best values currently available, although several of the abundances quoted are still controversial and the values are somewhat inconsistent with the ratios quoted above. Table III shows the abundances reported by the above authors, normalized to carbon=100. These values should be regarded as being typical of those for energies between 2-5 GeV per nucleon and are uncorrected for the generally small effect of geomagnetic cut-offs on nuclei of different Z/A ratios. Physically we would expect

TABLE III

(After Shapiro and Silberberg (1970))

Abundances of Heavy Primary Nuclei at the Top of the Atmosphere

(Normalized to Carbon = 100)

Element	Z	Relative Abundance	Element	Z	Relative Abundance
Lithium	3	16 ± 2	Sulphur	16	3.5 ± 1
Beryllium	4	11 ± 3	Chlorine	17	0.5 ± 0.3
Boron	5	27 ± 3	Argon	18	2 ± 0.5
Carbon	6	100	Potassium	19	0.6 ± 0.3
Nitrogen	7	27 ± 2	Calcium	20	2 ± 0.3
Oxygen	8	86 ± 4	Scandium	21	0.3 ± 0.2
Fluorine	9	2 ± 1	Titanium	22	2.0 ± 0.5
Neon	10	20 ± 2	Vanadium	23	1.0 ± 0.3
Sodium	11	3 ± 1.5	Chromium	24	3.5 ± 1.0
Magnesium	12	21 ± 2	Managanese	25	0.9 ± 0.3
Aluminum	13	2 ± 1	Iron	26	11.3 ± 1.4
Silicon	14	15 ± 2	Cobalt	27	<0.2
Phosphorous	15	$0.6^{+1.4}_{-0.5}$	Nickel	28	~0.2

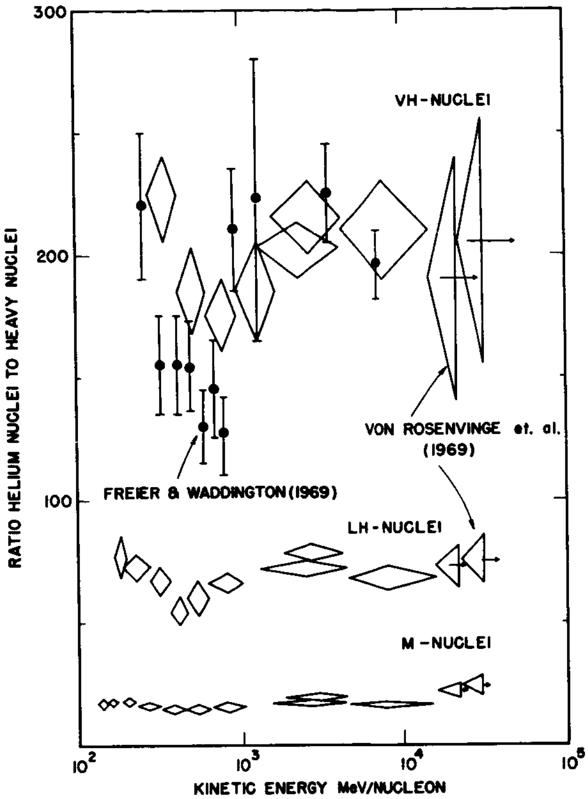

Figure 5. Measured values of the ratios of the abundance of helium to those of various groups of heavier nuclei, Waddington (1970).

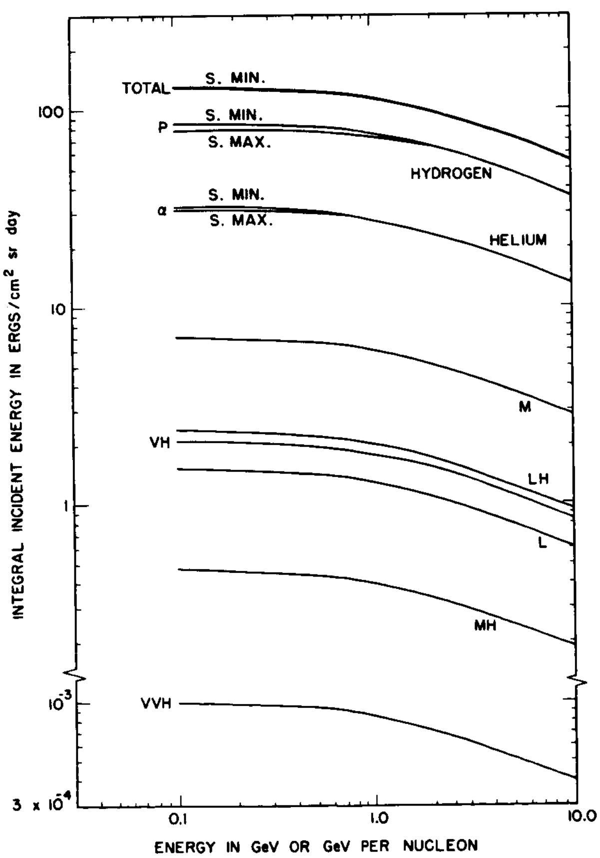

Figure 6. The integral energy intensities for cosmic ray nuclei.

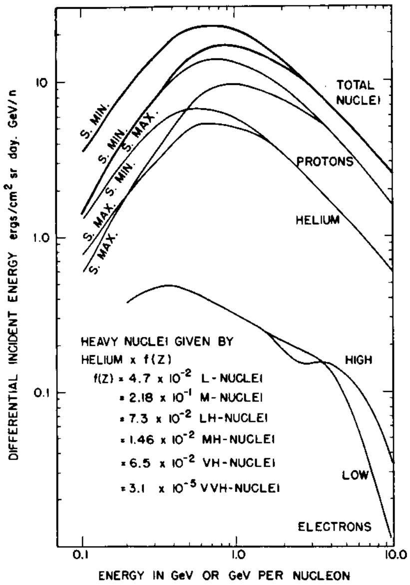

Figure 7. The differential energy intensities for cosmic ray nuclei and electrons.

radiation at the two locals. At sea level the particles are predominately muons, and the rate of energy deposition is small, while in space the deposition rate is considerably higher. This rate, which of course determines the dosage received by a sample immersed in the radiation, depends in a complex way on the charge, energy and nucleon interaction parameters of the incident particle. However, in no case can one envisage it being so high that the total energy of a component would be dissipated in traversing as little as one gram of material. Hence the average cosmic ray doses must always be very small, never exceeding a few rad/day. The localized dose, on the other hand, as pointed out before, may well be very considerable, since a single particle may release a great deal of energy in a small volume. As an extreme example, a nucleus of U^{238} having a total kinetic energy of 55 GeV has a range of 1 g/cm^2 in carbon of density 2.0 gm/cm^3. This energy is mostly dissipated by producing electrons of less than 10 keV that are absorbed within 10μm of the primary trajectory and hence in a volume of 1.5×10^{-6} cm . The energy deposited is thus equivalent to about 10^5 ergs/gm and gives a localized dose of 10^3 rads, which is sufficient to produce serious damage in many systems.

While this is admittedly an extreme example it is clear that these highly charged nuclei may well produce a line of damage. Similarly very energetic particles can produce either small volumes of damage, by nuclear interactions, or lines of damage, by production of cascades, nuclear or electromagnetic. The effects of producing these localized regions of damage in radiation sensitive systems do not appear to be well known and it seems important that further research should be undertaken to clarify our understanding of these problems.

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