

## Cosmic Ray Hazards in the Solar System

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### 1. Introduction

**I**N recent years, satellite, space probe, and balloon flights have given direct measures of the galactic cosmic ray intensity outside the Earth's atmosphere and in some cases outside the geomagnetic field. These and earlier measurements indicate that low and medium energy galactic cosmic rays are partially kept out of the inner solar system by interplanetary magnetic fields. The larger fields at times of solar maximum activity lead to corresponding lower cosmic ray intensities in the inner regions of the solar system, and it is found that an 11-yr cycle exists for these cosmic ray intensities. Superimposed on the 11-yr solar cycle are a number of irregular variations, such as Forbush decreases, which are presumably due to transient increases in the interplanetary magnetic field.

Ideally, we would like to know the cosmic ray intensity  $J$  as a function of the type of particle  $i$ , the energy  $E$  (or rigidity  $R$ ), the position in space  $r$  (relative to sun or earth), the time  $t$ , and the direction of the cosmic ray particles, so that  $J$  is a vector:

$$J(i, E, r, t)$$

At some future date we can expect to have exact information about interstellar cosmic rays near the solar system, and about the interplanetary (and terrestrial) magnetic fields as functions of time and position in the solar system. Then these can be fed into a transport program in a computer;

the product will be the cosmic ray spectrum as a function of time and position in the solar system. Since at present we have the necessary information only for very high-energy cosmic rays, and to some extent the terrestrial magnetic field, we shall have to be satisfied with a more fragmentary approach. (It is also possible that in the future it may be easier to measure the cosmic rays directly than to calculate their intensity!)

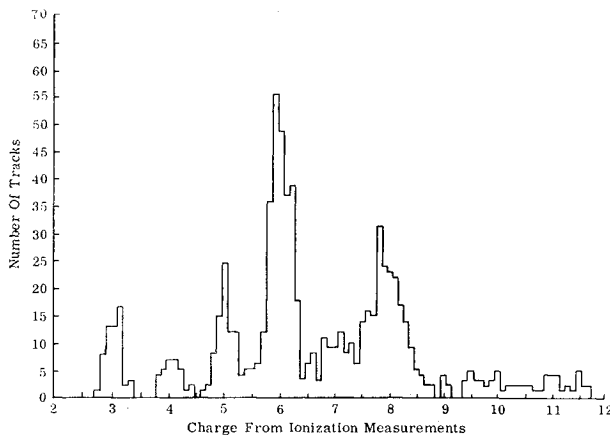
Thus, the topics to be covered in this paper are the direct measurements of cosmic ray energy and charge spectra near the Earth in Sec. 2, and in interplanetary space near the Earth in Sec. 3, followed by a discussion in Sec. 4 of the theory of the effects of planetary magnetic fields and atmospheres in modifying these spectra and of the interaction of cosmic rays with the moon's surface. In Sec. 5 we discuss the intensity of interplanetary cosmic rays in the outer solar system, partly using simple models of the interplanetary magnetic fields to give the resulting modulation of low-energy interstellar cosmic rays as a function of distance from the sun. The radiation doses will be estimated for the various regions in Sec. 6.

### 2. Cosmic Rays near the Earth

We consider two regions: 1) underground, sea level, and altitudes within the Earth's atmosphere and 2) outside the Earth's atmosphere but within the geomagnetic field.

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**Fig. 1** Frequency distribution of nuclear charge for 746 cosmic ray tracks with  $3 \leq Z \leq 11$ . It is evident that good resolution was achieved between the light elements ( $Z \leq 5$ ) and those with  $Z \leq 6$ . From Shapiro, Hildebrand, O'Dell, Silberberg, and Stiller.<sup>5</sup>

### Within the Earth's Atmosphere

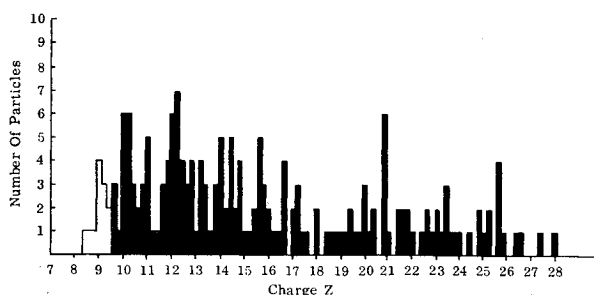
Measurements under 1 have provided vast quantities of information about cosmic rays with energies above about 1 Bev. Despite the geomagnetic field, very low-energy protons can penetrate to the top of the atmosphere near the geomagnetic poles; on the other hand, since the atmosphere has a depth of  $1000 \text{ g-cm}^{-2}$ , protons with energies of several hundred million electron volts do not penetrate more than part way through the atmosphere. Since a great part of our information about cosmic rays comes from measurements in the atmosphere, we shall first summarize the information about the nature of *primary* cosmic rays obtained in this way, because much of it is directly applicable to the space environment itself.

The average cosmic ray particle has a kinetic energy  $T$  of some few billion electron volts; at higher energies, which are relatively unaffected by interplanetary magnetic fields, the integral spectrum in terms of the total energy  $E = T + 0.94$  (Bev) is given by<sup>1</sup>

$$J(>E) \approx (0.2/E^{1.5}) \text{ cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1} \quad E \gtrsim 10 \text{ Bev} \quad (1)$$

This holds approximately up to energies of  $\sim 10^{18} \text{ ev}$ , and particles with energies up to  $10^{20} \text{ ev}$  have now been detected by extensive air shower measurements.<sup>2</sup> The omnidirectional total intensity is  $\sim 3 \text{ cm}^{-2}\text{-sec}^{-1}$ , for  $E > \sim 1.5 \text{ Bev}$ .

The primary cosmic rays probably consist of  $\sim 85\%$  protons,  $\sim 10\text{--}15\%$  helium nuclei,  $\sim 1\%$  nuclei with nuclear charge  $Z \geq 3$ , and  $\sim 3\%$  electrons<sup>3</sup>; other constituents expected to be present with small intensities include the other stable particles: positrons, antiprotons, various neutrinos, as well as gamma rays.<sup>4, 44</sup> In recent years emulsions have been exposed to cosmic rays at balloon altitudes with only



**Fig. 2** Charge spectrum of 178 cosmic ray heavy nuclei with  $Z \geq 10$ . From Neelakantan and Shukla.<sup>6</sup>

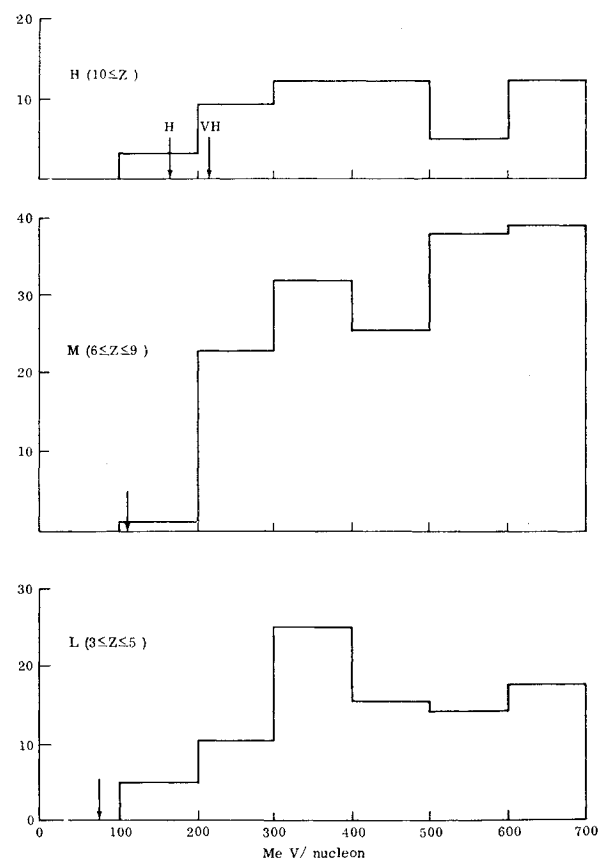
$2\text{--}3 \text{ g/cm}^2$  of atmosphere remaining above them, so that the corrections for fragmentation of heavy nuclei by the atmosphere before reaching the emulsion are very small. Thus, considerable confidence can be placed in these emulsion measurements of cosmic rays with  $Z \geq 2$ . The relative abundances of cosmic ray nuclei with  $3 \leq Z \leq 11$  determined by Shapiro et al.<sup>5</sup> are given in Fig. 1, and for  $10 \leq Z \leq 28$  determined by Neelakantan and Shukla<sup>6</sup> in Fig. 2; since there appears to be practically no component with  $Z > 28$ , the sum of the contributions from  $3 \leq Z \leq 28$  is the  $\sim 1\%$  of the primary flux just quoted. There is some uncertainty about whether the energy spectra of all the components have the same shape<sup>6, 7</sup>; the measurements of Koshiba et al.<sup>7</sup> presented in Fig. 3 suggest that the light nuclei Li Be B are relatively more abundant at lower energies.

The other important properties of primary cosmic rays are that they appear to be substantially isotropic in direction and constant in time, except for modulation by variable interplanetary magnetic fields (see Sec. 5).

### Outside Atmosphere but within Geomagnetic Field

In this region we consider the primary cosmic rays as modulated by the geomagnetic field, and the secondary ("albedo") particles arising from the interaction of cosmic ray primaries with the Earth's atmosphere, or with the earth itself (in this category would be high-energy muons produced in the Earth's crust by cosmic ray neutrinos coming right through the Earth from the opposite side); the expected muon fluxes,<sup>8</sup> however, are too small to concern us here.

The main features of the geomagnetic field shielding of the Earth from high-energy charged particles were explained many years ago in terms of a simple terrestrial magnetic dipole field, and more recently in terms of spherical harmonic



**Fig. 3** Energy spectrum of  $L$ ,  $M$ , and  $H$  nuclei at the top of the atmosphere. Arrows: air cutoff. Ordinate: number of particles in 100-Mev interval. From Koshiba, Lohrmann, Aizu, and Tamai.<sup>7</sup>

expansions (including higher multipole terms) fitted to the exact measured magnetic fields over the Earth's surface (see, for example, Sauer<sup>9</sup>). The simplest effect of the field is to produce a cutoff at a given magnetic latitude of cosmic rays with magnetic rigidity less than a definite value. Here, the magnetic rigidity has its usual definition of momentum to charge ratio:  $R = pc/e$ , where  $p, e$  are particle momentum, charge, respectively, and the total energy  $E = (R^2 c^2 + M^2 c^4)^{1/2}$ . It has been found, however, by balloon, rocket, and satellite observations that the geomagnetic cutoffs are not explained accurately by such ground level fields alone. Akasofu et al.<sup>10</sup> have found that the observed steady and magnetic storm cutoffs can be explained by combining the observed finite extension of the geomagnetic field (the "geomagnetic cavity" in the solar wind) and a physically reasonable ring current at several Earth radii (cf. Heppner et al.<sup>11</sup> and Webber<sup>12</sup>).

More directly, we now have extensive cosmic ray measurements within the geomagnetic field as a function of latitude, longitude, altitude, and also limited periods of time. In the most extensive measurements to date, Lin, Venkatesan, and Van Allen<sup>13</sup> used a shielded Geiger tube on Explorer 7 to measure the cosmic ray intensity above 30 Mev during the period October 1959–February 1961, at altitudes of 550–1100 km. There was a sharp rise in counting rate whenever the satellite entered the radiation belts of the Earth, but it was possible to discriminate against the belt radiation by comparing the counts from the shielded Geiger tube and another unshielded one. The resulting intensity is then the sum of the primary cosmic rays and any charged particle secondaries produced in the atmosphere. In this work, as in much of the recent geomagnetic region research, Lin et al. used the McIlwain<sup>14</sup> magnetic shell parameter  $L$ , defined approximately as the equatorial radius (measured in Earth radii) of the line of force on which a particular particle is mirroring; Stone<sup>15</sup> has refined the original definition of  $L$ . Lin et al.<sup>13</sup> found (Fig. 4) that the charged particle intensity increases monotonically with increasing  $L$  and is accurately constant within experimental error for  $L > 2.9$ , and that the omnidirectional intensity is  $J_0 = 2.0 \text{ cm}^{-2}\text{-sec}^{-1}$  at all high latitudes and decreases to  $0.56 \text{ cm}^{-2}\text{-sec}^{-1}$  at the equator. They also find that the charged particle contribution from the upward moving (splash) albedo intensity  $J_{AS}$ , and from the re-entrant albedo  $J_{AR}$  from reactions in the atmosphere on the opposite side of the Earth (see, e.g., Ray<sup>16</sup>), is comparable to that from the primaries  $J_P$ . Thus, by using an earlier value for the interplanetary  $J_{IP}$ , and the fact that for large  $L$  their Explorer 7 measurements covered 70% of the total solid angle:

$$J_0 = J_P + J_{AS} + J_{AR} \quad J_P = 0.7 J_{IP} \quad (2)$$

$$J_{IP} = 1.8 \text{ cm}^{-2}\text{-sec}^{-1}$$

they derived the total albedo contribution

$$J_{AS} + J_{AR} = 0.74 \text{ cm}^{-2}\text{-sec}^{-1} = 0.59 J_P \quad (3)$$

An important (but indirectly estimated) result was that during this period the primary spectrum had less than 3% of its total intensity in the rigidity range  $R < 2.2 \text{ Bv}$  (units of billion volts), i.e., proton  $T = 1.46 \text{ Bev}$ . Since the cutoff for protons at high  $L$  is down to an energy of some tens of million electron volts, it is probable that this result can be taken over to the interplanetary case near the Earth:

$$J_{IP}(T > 1.46 \text{ Bev}) > 0.97 J_{IP} \quad (4)$$

Of course, as far as radiation hazards near the Earth are concerned, it is the total intensity  $J_0$  of Eq. (2) which is important, but for predicting the radiation near other planets (Sec. 4) it is important to distinguish the primary ( $J_P$ ) and albedo ( $J_{AS}, J_{AR}$ ) contributions.

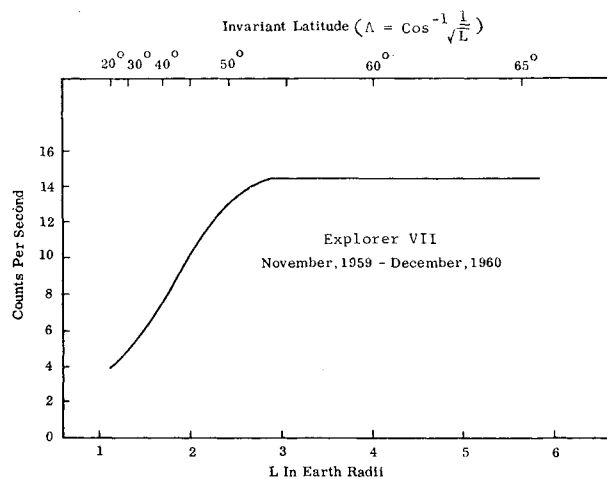


Fig. 4 Dependence of average charged particle counting rates on  $L$ . Adapted from Lin, Venkatesan, and Van Allen.<sup>13</sup>

The other major component of the near-Earth radiation is the neutron flux, which derives entirely from reactions of the primaries with the atmosphere. Since the primary spectrum, atmospheric composition, and density are known moderately well, it is possible to calculate the expected neutron flux. Lingenfelter's calculations<sup>17</sup> of the albedo neutron spectrum at several geomagnetic latitudes, for both solar maximum and solar minimum, are presented in Fig. 5. The earlier results of Hess et al.<sup>18</sup> in Fig. 6, for the neutron spectrum at different distances from the Earth but all at the geomagnetic equator, show the expected decrease in neutron intensity as the distance increases to several Earth radii. They note that thermal neutrons with energies less than  $0.66 \text{ ev}$  will be trapped in the Earth's gravitational field and that many will decay in orbit before they return to Earth (see Fig. 7).

The recent experimental measurements<sup>19–22</sup> of the neutron flux above the atmosphere differ by a factor of 3 among themselves. The detectors used give integrated spectra over many decades of energy, so that it is possible to approximate the neutron spectrum only very crudely. Also, part of the results of each Atlas flight were not useful because of the large background due to secondary neutrons produced in

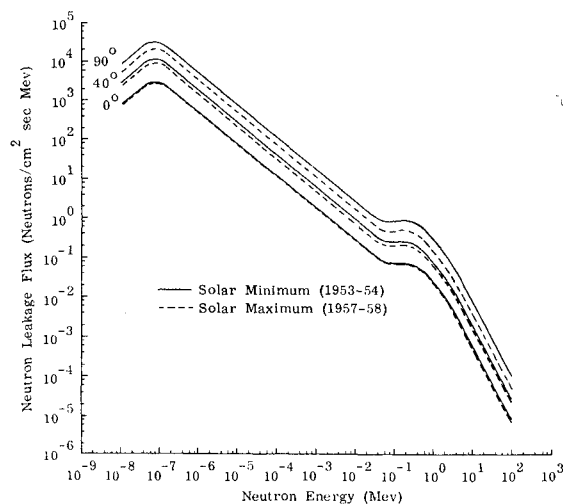
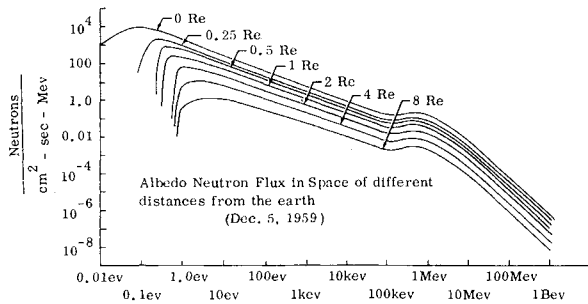


Fig. 5 The cosmic-ray neutron leakage flux spectrum at  $0^\circ$ ,  $40^\circ$ , and  $90^\circ$  geomagnetic latitude for solar minimum and solar maximum. The spectral shape above  $10 \text{ Mev}$  is from the measurements of Hess et al. (1959). From Lingenfelter.<sup>17</sup>



**Fig. 6 Neutron energy spectra in space at different distances from the Earth above the geomagnetic equator. Distance unit is radius of the Earth ( $R_E$ ). The 0  $R_E$  curve is for the top of the atmosphere, which is roughly 100 km. From Hess, Canfield, and Lingenfelter.<sup>18</sup>**

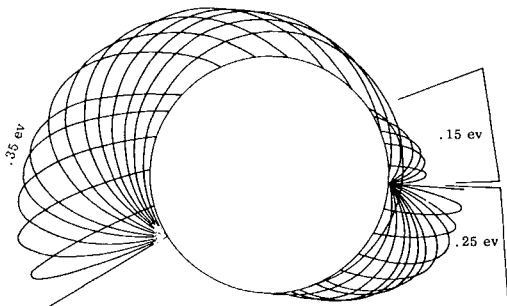
the rocket and payload by the protons in the radiation belt. Thus, although at present the experiments are consistent with the calculations of the shape and magnitude of the albedo neutron spectrum to within the experimental differences, more measurements are necessary to check the validity of the theory.

### 3. Cosmic Ray Measurements in the Inner Solar System

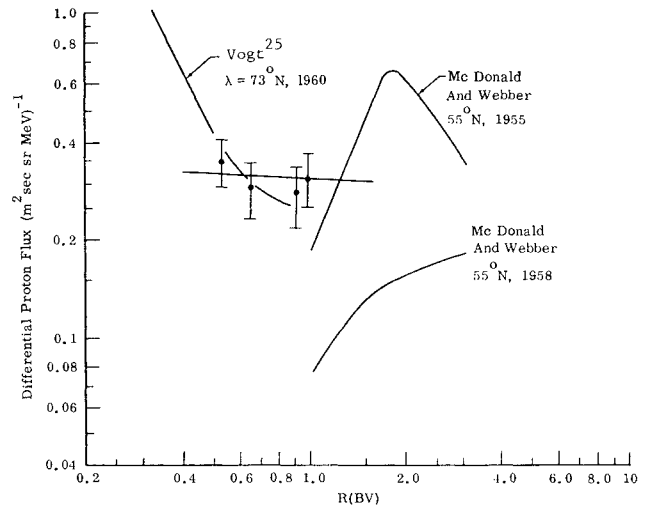
Recent cosmic ray measurements near the orbits of Earth and Venus are discussed. [The earlier Pioneer 5 (1960), etc., results are not considered here.]

Measurements were made by Mariner B over a path of  $360 \times 10^6$  km between the orbits of Earth and Venus and over a period of some 130 days (August 27, 1962–January 3, 1963). The data available to date<sup>23</sup> indicate an average interplanetary cosmic ray intensity of  $3 \text{ cm}^{-2}\text{-sec}^{-1}$ .

The Explorer 12 and 14 cosmic ray data are also only partly available at present. Explorer 12 had an apogee of 80,000 km on the day side of the Earth and was outside the geomagnetic field for more than half the time in each orbit,<sup>24</sup> during which time it measured the interplanetary value of the cosmic rays over a 120-day period beginning August 16, 1961. Since the cosmic rays above 600 Mev produce many secondaries by nuclear interactions in the spacecraft and the detectors, large corrections had to be made by Bryant et al.<sup>24</sup> to find the low-energy differential spectrum given in Fig. 8; there is good agreement with the high geomagnetic latitude balloon results of Vogt<sup>25</sup> from the period August–September 1960 and Meyer and Vogt<sup>26</sup> from the period July–August 1961. However, in comparison with the Lin et al.<sup>13</sup> measurements, which ended only some 6 months earlier, their results indicate considerably more low rigidity cosmic rays. It is possible<sup>26</sup> that the particles with  $T < 200$  Mev are of solar origin.



**Fig. 7 Orbits of neutrons gravitationally trapped in space near the Earth. Three sets of orbits are shown for neutrons of three different energies:  $E_n = 0.35, 0.25$ , and  $0.15$  eV. Adapted from Hess, Canfield, and Lingenfelter.<sup>18</sup>**



**Fig. 8 Low-energy primary cosmic ray spectrum measured by Explorer XII. The points with bars, and the figure, are from Bryant, Cline, Desai, and McDonald.<sup>24</sup>**

The integral intensity found on August 18, 1961 by Bryant et al.<sup>24</sup> was  $J_{IP}(> 600 \text{ Mev}) = 1.7 \text{ cm}^{-2}\text{-sec}^{-1}$ .

### 4. Cosmic Rays and Secondaries near Moon and Planets

Since present evidence supports an essentially isotropic flux of interplanetary cosmic rays, the intensity incident on the moon's surface will be just half the free space omnidirectional intensity. The primaries interact with the lunar surface to produce secondary neutrons,<sup>27</sup> protons,<sup>28</sup> alpha particles,<sup>28</sup> pions, muons,<sup>29</sup> electrons,<sup>28</sup> gamma rays,<sup>28, 30, 44</sup> etc. From the point of view of scientific information, all these should be measured. One recent suggestion<sup>29</sup> is that it might be possible to infer the density inside a lunar mountain by measuring secondary muons of energies  $10^3$ – $10^5$  Bev traversing the mountain. From the point of view of radiation hazards, only the neutron and gamma ray intensities appear to be significant.

Lingenfelter, Canfield, and Hess<sup>27</sup> calculated the neutron leakage (or albedo) spectrum at the lunar surface and found that the neutron intensity depended strongly on the chemical composition (particularly the relative hydrogen abundance) (see Fig. 9). The total neutron flux is of the order of  $10 \text{ cm}^{-2}\text{-sec}^{-1}$ .

The gamma ray flux from the lunar surface is estimated by Hayakawa<sup>28</sup> to be  $\sim 0.5 \text{ cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1}$  (1–2 Mev) and  $\sim 0.03 \text{ cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1}$  ( $\sim 100$  Mev).

In the case of the planets, we can draw upon the extensive measurements and theory for the Earth. Obviously, planetary magnetic fields will modulate the interplanetary cosmic ray flux before it reaches the planetary atmosphere. At present, the only direct planetary magnetic field measurements we have are the Mariner B results<sup>23</sup> indicating that the Venusian magnetic field on its sunward side does not extend out to a distance of 40,000 km from the center of Venus; the magnetic field is therefore probably weaker than the Earth's, and this is consistent with a slow rotation rate such as is suggested by other observations.

The albedo neutrons and gamma rays emerging from the planetary atmosphere can be calculated as for the terrestrial and lunar cases (see Sec. 2 and the foregoing). Here, we consider the passage of the cosmic rays and their secondaries down through the atmosphere. In the case of Mars, the atmosphere is considerably thinner than the Earth's, so that the cosmic ray secondaries might possibly be a hazard to manned surface activities. If it is assumed that the nuclear composition of the Mars atmosphere has approximately the

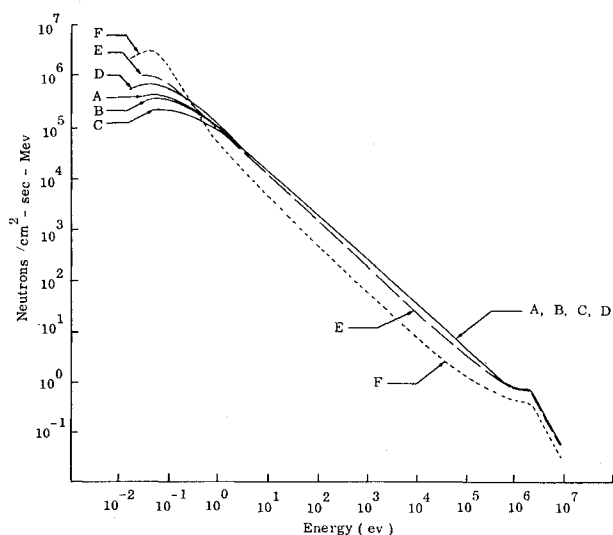


Fig. 9 The calculated neutron equilibrium leakage spectrum for the lunar surface for compositions *A*, chondritic material; *B*, chondritic material with a 10% increase in the total  $1/v$  capture cross section; *C*, with a 50% increase in  $1/v$  capture; *D*, with a 35% decrease in  $1/v$  capture; *E*, chondritic material with 0.1 H/Si atom; and *F*, with 1.0 H/Si atom. From Lingenfelter, Canfield, and Hess.<sup>27</sup>

same neutron/proton ratio as the Earth's atmosphere (which will be the case if the Martian atmosphere is predominantly nitrogen, as currently believed), it is possible to take over, in an approximate fashion, many of the calculations<sup>17, 31, 32</sup> and measurements<sup>33, 34</sup> made for the terrestrial atmosphere. As an example of some of the terrestrial information available, we present in Fig. 10 Lingenfelter's<sup>17</sup> recent calculations of the neutron production rate in the terrestrial atmosphere at solar minimum, using a multigroup diffusion machine program to find the rate as a function of geomagnetic latitude and epoch of the solar cycle.

Yagoda<sup>35</sup> and Fink and Milford<sup>36</sup> have used the terrestrial information to estimate the neutron flux at various depths in the Martian atmosphere on the assumption that Mars does not have a large magnetic field. The approximate

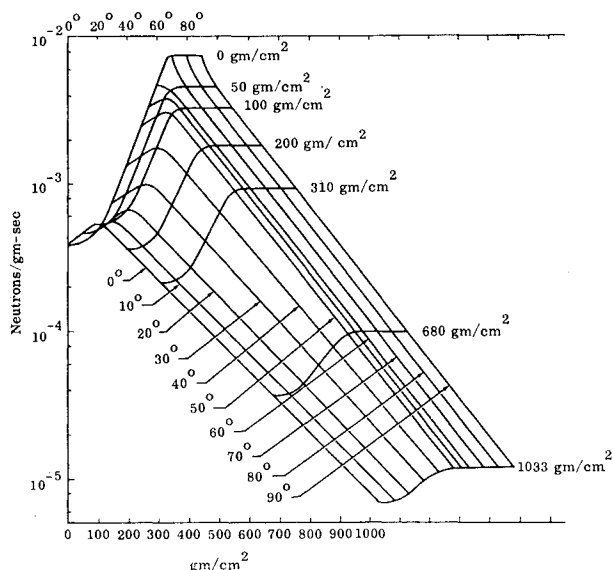


Fig. 10 The solar minimum cosmic-ray neutron production rate in neutrons/g sec as a function of altitude,  $g/cm^2$ , and geomagnetic latitude, normalized to a total production rate of 1 neutron/ $cm^2$  column of air/sec at the geomagnetic pole. From Lingenfelter.<sup>17</sup>

neutron, proton, muon, and electron fluxes given by Fink and Milford<sup>36</sup> are shown in Fig. 11. Yagoda<sup>35</sup> has also pointed out that the rate of "star" production in nuclear emulsions at the surface of Mars would be some orders of magnitude larger than that at the Earth's surface.<sup>37</sup>

As far as radiation near other objects in the solar system is concerned, for those with little or no atmosphere (Mercury, Pluto, all satellites except Saturn's Titan, asteroids), the high-energy cosmic radiation at the surface will be comparable with that at the moon, but the low-energy cosmic radiation is expected to have a larger intensity for the outer planets (Sec. 5). Thus, the total primary and secondary radiation will be larger than in the lunar case. For those objects with appreciable atmospheres (remaining seven planets, Titan), most of the atmospheres are probably so thick that the radiation at their surfaces produced by cosmic radiation is expected to be less than that at the surface of the Earth (this would not be true for Titan), so that no radiation hazard is presented except in regions near the upper parts of these atmospheres. Also, the Jupiter magnetic field appears to be intense enough and extensive enough to provide extremely strong shielding from cosmic rays and solar flare particles over large regions of the planet.

## 5. Cosmic Rays in the Outer Solar System

There exist no direct measurements of cosmic rays in the region outside the Earth's orbit. Our sources of information about such cosmic rays are as follows.

### Meteorites

These are exposed to cosmic radiation in interplanetary space from the time that they are formed as entities not

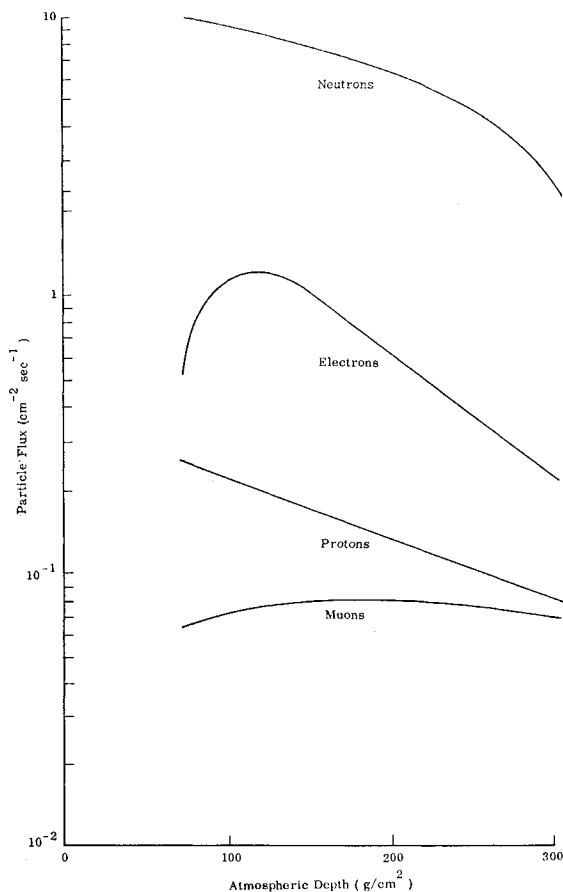


Fig. 11 Particle fluxes produced by cosmic rays as a function of depth in the Martian atmosphere. From Fink and Milford.<sup>36</sup>

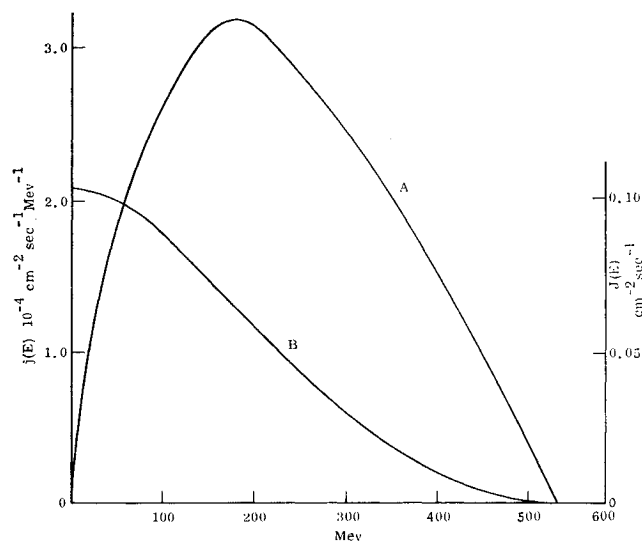


Fig. 12 A: Differential spectrum of low-energy cosmic rays ( $\text{cm}^{-2} - \text{sec}^{-1} - \text{Mev}^{-1}$ ), B: Integral spectrum of low-energy cosmic rays ( $\text{cm}^{-2} - \text{sec}^{-1}$ ). From Ferentz and Milford.<sup>42</sup>

shielded effectively by surrounding matter. On approaching the Earth, they normally lose some of their outer layers during atmospheric entry, and of course in some cases fragmentation occurs. However, by measuring the isotopic changes within the meteorite caused by the cosmic ray bombardment, it is possible to estimate the time average of the cosmic ray intensity in the regions in which the meteorite moved. In particular, since meteorites appear to have high eccentric orbits, measured cosmic ray induced radioactivities of short life (weeks) must have been produced near the region of the Earth's orbit, whereas those of long life (years) must have been produced over the entire orbit of the meteorite. By measuring the ratio of  $\text{Ar}^{37}/\text{Ar}^{39}$  ( $\text{Ar}^{37}$ : 35 day half-life;  $\text{Ar}^{39}$ : 325 year half-life) for a particular meteorite, Stoenner et al.<sup>38, 39</sup> and Fireman et al.<sup>40</sup> were able to infer that the average cosmic ray flux near the Earth's orbit, during the period of several weeks just before the meteorite fell, was within a factor of 2 of that averaged over the meteorite's orbit, which presumably extended out about as far as the asteroid belt at 2.8 a.u., over the last few hundred years. Although there are some weaknesses in generalizing this result, it is at least in the nature of a direct measurement. These results apply to cosmic rays integrated over the energy range  $\sim 0.2$ –2 Bev.

### High-Energy Cosmic Rays

With some plausible assumptions, it can be argued that the cosmic rays of energies of some few billion electron volts and higher probably traverse the solar system with little change in intensity from the interstellar value. Thus the measured local values can be adopted as representative of the interplanetary high-energy cosmic rays. This argument is supported strongly by the fact that the high-energy cosmic rays are practically isotropic and constant in time, whereas the modulating magnetic fields in interplanetary space fluctuate with the solar cycle.

### Theoretical Estimates of the Intensity of Low-Energy Cosmic Rays

As mentioned in the Introduction, if we knew the interstellar cosmic ray spectrum  $J_{IS}$  in detail and the interplanetary magnetic field as a function of time  $t$  and position  $r$  in the solar system, then we could calculate the modulation of  $J_{IS}$  to find  $J_{IP}(i, E, r, t)$ . In the following, we make gross approximations to this calculation for particles with rigidities

less than 2Bv. Interstellar low-energy cosmic rays must be produced in at least two ways:

1) Injection from stable and unstable stars. We now have direct information about the rate of emission of solar high-energy particles for the period 1956–1961. From Malitson and Webber's<sup>41</sup> summary in the Solar Proton Manual, we can estimate that over a solar cycle the average particle emission by the sun is at the rate  $\sim 10^{29} \text{ sec}^{-1}$  ( $T > 30 \text{ Mev}$ ),  $\sim 10^{28} \text{ sec}^{-1}$  ( $T > 100 \text{ Mev}$ ). If all  $10^{11}$  stars in the galaxy injected particles at the solar rate, the total stellar injection rate would be equivalent to injection in the region of the galactic plane at a rate of  $\sim 10^{-26} \text{ cm}^{-3} \cdot \text{sec}^{-1}$  ( $> 30 \text{ Mev}$ ),  $\sim 10^{-27} \text{ cm}^{-3} \cdot \text{sec}^{-1}$  ( $> 100 \text{ Mev}$ ). Of course, since there is an extremely wide range of stellar types (including supernovae), and probably of particle injection rates, such estimates may be incorrect by orders of magnitude.

2) Production by collisions of high-energy cosmic rays with the interstellar gas. Ferentz and Milford<sup>42</sup> have used the estimated intensity of 1–30 Bev interstellar cosmic rays to calculate the production spectrum of recoil protons in the range 0–500 Mev. They find an integrated production rate of  $\sim 10^{-26} \text{ cm}^{-3} \cdot \text{sec}^{-1}$ , which should be correct to an order of magnitude for the 1–30 Bev primaries considered (the contribution from  $< 1$  Bev primaries will be added later). By combining the production spectrum with the slowing lifetimes<sup>43</sup> of protons in the interstellar gas, the intensity of these 0–500 Mev protons is found to be  $\sim 0.1 \text{ cm}^{-2} \cdot \text{sec}^{-1}$ , with the spectrum shown in Fig. 12.

It is possible that other processes, such as acceleration by interstellar magnetic fields, may contribute significantly to the production of low-energy cosmic rays. Hatanaka et al.<sup>45</sup> have hypothesized a very high intensity of low-energy cosmic rays in order to explain the heating of interstellar gas clouds, but at present there is no compelling reason to accept such high values.

As a result of the foregoing discussion of the production of low-energy interstellar cosmic rays, we see that we do not have enough information yet about the low-energy particles bombarding the outer regions of the interplanetary magnetic fields. Turning now to the motion of these interstellar cosmic rays in the interplanetary magnetic field, we find that the information about the field, from the modulation<sup>12</sup> of 0.1–10 Bev solar and galactic cosmic rays observed at the Earth, and from measurements of the field itself near the Earth's orbit,<sup>11, 23</sup> is not sufficient to uniquely define the field away from the Earth's orbit. However, it is possible to set up a simple interplanetary magnetic field model, and then calculate the modulation as follows.

For simplicity, McCoy and Milford<sup>46</sup> adopt Parker's<sup>47</sup> diffusion model in which locally ordered regions of the magnetic field act as scattering centers. If these scattering centers move outward with the solar wind, a steady state is reached with the cosmic ray intensity in the solar system depressed below the value in interstellar space. The solar wind is assumed to be radial and constant out to the position of the shock transition between the interplanetary and interstellar plasmas. Following Parker<sup>48</sup> and Axford, Dessler, and Gottlieb,<sup>49</sup> we adopt the size  $l$  of the scattering centers as  $l = l_0(r)^{2/3}$  and the average magnetic field  $B$  within a scattering center as  $B = B_0/r$ , where  $r$  is the distance from the sun. We calculate the modulation produced by this spherically symmetrical field on the assumption that it extends out to a distance of 50 a.u. The shock region will affect the lowest-energy particles, but apart from this, the major part of the modulation occurs, for example, inside the orbit of Jupiter (5 a.u.) for protons with  $T < 200 \text{ Mev}$ , so that it does not matter too much on this model where the shock region is, provided that it is not within 3 or 4 a.u. from the sun. In a paper just published, Morris, Clark, and Wilson<sup>51</sup> conclude that the interstellar magnetic field is probably much smaller than suggested by earlier results. This would move the shock region further out in the solar system.

Adopting values corresponding to near solar-cycle maximum  $B_0 = 3 \times 10^{-5}$  gauss a.u.,  $l_0 = 10^{-2}$  a.u.<sup>1/3</sup>, and  $v = 500$  km/sec,<sup>11, 23, 50</sup> we find the modulation factor  $J(r \text{ a.u.})/J(50 \text{ a.u.})$  as a function of particle energy and position in the solar system<sup>46</sup>; the results for protons and iron nuclei are presented in Figs. 13 and 14. It can be seen that, if this model is correct even within orders of magnitude, no interstellar protons with energies less than 10 or 20 Mev would penetrate into the solar system as far as the orbit of Jupiter. Also, on this model, iron nuclei are modulated more than protons of the same rigidity, but less than protons of the same energy per nucleon.

## 6. Radiation Dose Rates from Cosmic Rays in the Solar System

In the previous sections we have summarized the known and estimated charge and energy spectra of cosmic rays in the solar system. The corresponding approximate dose rates can be calculated from various conversion formulas.<sup>52-54</sup> The physical dose in rep (roentgen equivalent, physical) or rad is multiplied by the relative biological effectiveness (RBE) to give the dose equivalent in rems (roentgen equivalent, men). The RBE factors are reasonably well known for protons, light nuclei, neutrons, electrons, and x and gamma-rays, but there is still considerable uncertainty about the effects of heavy nuclei. Thus, although the contribution of heavy primaries to the total ionization per gram per second is only about 5%, their actual ionizing tracks when they occur have physical doses of the order of  $10^4$  roentgen in their cores. Since the bulk of this ionization occurs within a column only some few microns thick, i.e., comparable in size to living cells, it is probable that the occasional lethal hit on irreplaceable cells is much more important than the over-all ionizing effects from the bulk of the cosmic ray intensity. For this reason, until the radiation effects of the

heavy primaries are better understood, their radiation effect is quoted in hits  $\text{cm}^{-2} \text{sec}^{-1}$ .

We note that the present permissible whole body doses for occupational workers (whole population) are 5(0.2) rem/yr, 0.1(0.003) rem/week, respectively.<sup>52</sup> These values do not include doses from medical and background exposure (latter is our prime concern here). In practice, in exploratory missions there will be more consideration given to the total accumulated dose, which should not come to more than 100-200 rems if serious radiation sickness is to be avoided. It is interesting to note that the dose rate due to cosmic rays at sea level is  $\sim 0.001$  rem/week and at supersonic transport altitudes (20 km) is  $\sim 0.2$  rem/week.<sup>55</sup>

For cosmic rays outside the strong field part of the geomagnetic cavity, the dose rate from the over-all ionization produced in an unshielded human being is  $\sim 0.5$ -1 rem/week,<sup>54</sup> and this rate diminishes as the point considered moves into the denser parts of the geomagnetic field.

It will be recalled (Sec. 2) that at points just outside the atmosphere the albedo flux of charged particles and neutrons becomes appreciable: the dose from the cosmic ray plus secondary charged particles is about the same as the free space dose, and, from the albedo neutrons, it is  $\sim 0.1$  rem/week. The dose rates near the moon's surface are about the same for the charged particles and neutrons as for the extra-atmospheric case. At the surface of Mars the dose rate<sup>55, 56</sup> is possibly  $\sim 0.2$  rem/week.

In regions far out in the solar system, Sec. 5 suggests that we might find an appreciable intensity of cosmic rays in the 0-300 Mev region, which would make the total unshielded dose rate  $> 1$  rem/week. However, these lower-energy cosmic rays can be usefully reduced by reasonable size shields ( $\sim 20$  g-cm<sup>-2</sup> say). In addition, these thin shields can absorb the heavy nuclei or convert them rather efficiently to lighter nuclei of lesser danger. On the other hand, quite thick shielding ( $\sim 200$  g-cm<sup>-2</sup>) is required to significantly re-

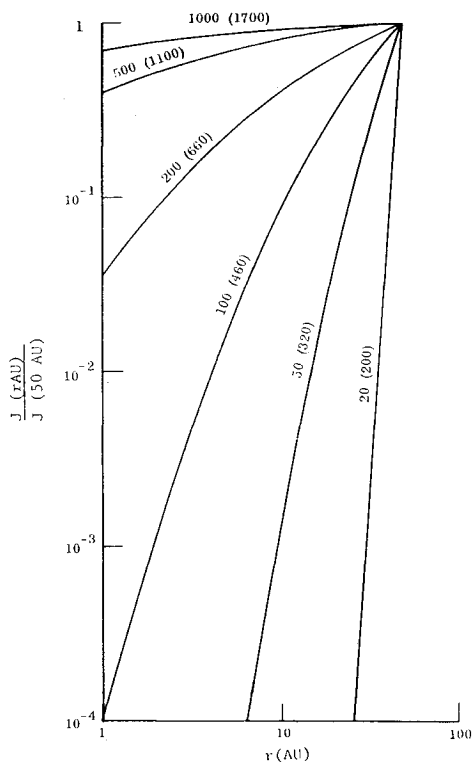


Fig. 13 Modulation of galactic cosmic ray protons calculated by means of a simple model of the interplanetary magnetic field. The curves are labeled  $T(R)$ , where  $T$  is the kinetic energy/nucleon in Mev,  $R$  the rigidity in Mv. From McCoy and Milford.<sup>46</sup>

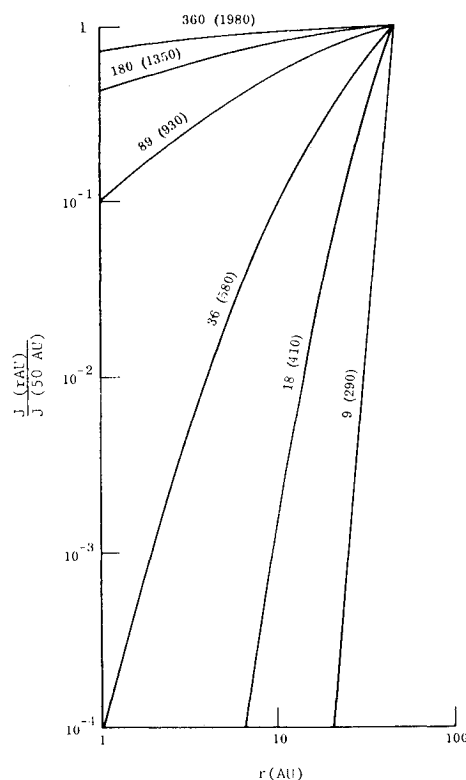


Fig. 14 Modulation of galactic cosmic ray iron nuclei calculated by means of a simple model of the interplanetary magnetic field. The curves are labeled as in Fig. 13. From McCoy and Milford.<sup>46</sup>

duce the intensity and dose rate of average cosmic rays (thinner shielding tends to produce harmful secondaries as well as slowing some of the primaries to energies at which they give larger dose rates).

As far as damage from heavy primaries is concerned, Yagoda et al.<sup>56</sup> and Curtis and Smith<sup>57, 58</sup> give some experimental evidence that these primaries may not constitute as large a hazard as had been thought, but much more work is required before we shall know the exact radiation effects of these heavy primaries.

In summary, the known hazard presented by cosmic rays is appreciable only for long term space missions, such as one or two year trips to planets, or possibly for bases on the moon or Mars, when unshielded total doses of  $\sim 100$  rem may be accumulated. Possible unknown hazards might arise from heavy nuclei in the inner solar system, or, in future missions, from high intensities of light or heavy nuclei in the outer solar system; but shielding should not be too difficult for these cases (see recent articles on shielding<sup>54, 59</sup> and the calculation of radiation doses on space missions).<sup>60</sup>

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## Inelastic Atomic Collisions in Plasmas

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### Introduction

THE collision processes that play the greatest role in the excitation and ionization state of a typical thermal plasma are excitation, ionization, charge transfer, and recombination of atoms, molecules, and ions. In this paper, we shall restrict the discussion to excitation and ionization collisions involving electrons, atoms, and ions at thermal and near thermal energies. Denoting an atom or ion by  $A$ ,  $B$  and an electron by  $e$ , the processes are then

$$e + A(r, n) \rightarrow e + A(r, n') \quad (1a)$$

$$e + A(r, n) \rightarrow (r' - r + 1)e + A(r', n') \quad r' > r \quad (1b)$$

$$A(r, m) + B(s, n) \rightarrow A(r, m') + B(s, n') \quad (2a)$$

$$A(r, m) + B(s, n) \rightarrow A(r', m') + B(s', n') + (r' + s' - r - s)e \quad (2b)$$

$$r' \geq r, s' \geq s, r' + s' - r - s \geq 1$$

$r, s, r', s' = -1, 0, 1, 2 \dots =$  charge on atom or ion

$m, n, m', n' =$  state of atom or ion

Although formally all of the foregoing processes are included under (2b), the differences between electron (1) and heavy particle (2) collisions, and between excitation (a) and ionization (b) collisions are large enough to require separate

discussions. It is also usual to distinguish the cases where at least one atom is neutral ( $r = 0$  and/or  $s = 0$ ) from the other cases.

Since "thermal" plasma temperatures are only some few electron volts, the collision cross sections are needed in energy ranges determined by Maxwell distributions which, in many cases, will be declining rapidly with energy at the threshold for excitation or ionization of the ground state of typical atoms. However, for excited states of the atoms, the threshold energies are smaller by factors of 10 to 1000, and it is now the atomic cross section that is declining in the region where the velocity distributions peak. These points are illustrated in Fig. 1. It can be seen that the only part of the ground state cross section which contributes appreciably to the excitation rate is the part just above threshold, whereas for an excited state, the region of the cross section above its maximum will be most important. As is well known, the current state of collision theory and experiment tends to give particularly poor accuracy for the threshold, so that much of our discussion will be concerned with the accuracy available for various cross sections in the threshold region.

We begin with a discussion of some of the collision parameters for a thermal plasma, with some asymptotic cross sections used to illustrate typical collision processes. The following two sections will treat firstly electron collisions with ground and excited states of hydrogen and then collisions with other atoms and ions. Finally, there will be a discussion of heavy particle collisions treated more briefly than the electron case because the collision rates involved are usually smaller and therefore play a smaller role in the state of the plasma.

### Effective Cross Sections in a Thermal Plasma

For almost all plasmas of interest, the particle velocities in the plasma remain in equilibrium, obeying the Maxwell-

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