X-611-66-114

NASA TM X-55513

PROPAGATION OF COSMIC RAY NUCLEI IN COSMIC RAY SOURCES, INTERSTELLAR SPACE AND SOLAR SYSTEM

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NASA — GODDARD SPACE FLIGHT CENTER
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N. Durgaprasad*

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Abstract

Simultaneous intensity measurements of protons, helium, and heavy nuclei can be used to describe the effects on the source energy spectrum of solar modulation and diffusion occurring in source regions and in interstellar space. The energy spectra of heavy nuclei ($Z \geq 10$) have been determined in the energy region 200 - 700 Mev/nucleon for the year 1961 and compared with similar data obtained for protons, α-particles, and heavy nuclei during the years 1961 and 1963. These results have indicated that the observed intensities could be adequately explained by the following: (a) the modulating mechanism as described by a model given by Parker compared with the electric deceleration model of modulation, (b) a source differential rigidity or total energy spectrum rather than a kinetic energy spectrum having an exponent of 2.35 (as derived

*NAS-NASA Postdoctoral Research Associate on leave from Tata Institute of Fundamental Research, Bombay, India.

from experimental data available in the high energy range 10^{10}-10^{14} eV/nucleon, that is little affected by solar modulation) and (c) a path length of interstellar matter traversed that is decreasing or constant with decreasing energy for energies $\lesssim$15 GeV/nucleon.

Author

Introduction

The energy spectra of the low energy cosmic ray nuclei observed at the earth depend on (a) the energy spectrum of nuclei emanating from the source (b) the propagation of these nuclei in the interstellar space (diffusion and acceleration) and (c) the modulation of the energy spectrum in the vicinity of the solar system. These various effects could be delineated from a systematic study of the simultaneous measurement of the energy spectra and intensity of various components of the cosmic radiation as a function of time. Protons and helium nuclei have the same energy loss per nucleon for particles of the same velocity, but have charge to mass (Z/A) ratios that differ by a factor of two. Therefore these two species of nuclei can be used to separate the rigidity and velocity effects of solar modulation. α-particles and heavy nuclei have a Z/A ratio that is almost 0.5, but have different rates of energy loss $\left(Z^2/\beta^2 c^2\right.$ where βc is the velocity of the nucleus$\left.\right)$; thus their relative intensities are similarly affected by solar modulation, but depend to a large extent on their diffusion in interstellar space and source regions.

Systematic studies of the differential energy and intensity spectra began in the year 1961 for the protons and helium nuclei components [see, e.g., Fichtel et al, 1964]; the earlier data on such energy spectra were obtained from detectors flown in balloons under a few g/cm^2 of atmospheric depth and are subject to uncertainties in the extrapolation procedures adopted. The heavy nuclei component was recently studied by Lim and Fukui [1965] and Fichtel et al. [1965] using emulsions flown in satellites and rockets during the year 1963. We report here those observations made on the energy spectra of cosmic ray nuclei of charge $Z \geq 10$ in the energy interval 200-700 MeV/n during the period 1961. Measurements of the energy spectra for proton and helium nuclei for this period have been previously made by Fichtel et al. [1964]. This paper is referred to hereafter as paper I. These observations are combined with the present ones and with similar spectra obtained during 1963 for the heavy nuclei, α-particles, and protons in order to expand on the three aspects mentioned previously.

Experimental Details

A stack of nuclear emulsions exposed to a mean altitude of ~ 2.4 g/cm^2 of residual atmosphere in a balloon near Fort Churchill during 1961 for a period of ~ 10 hours is used for the present purpose. The details regarding the stack size, the flight curves, description, and orientation of the stacks before and during the flight are described in paper I.

The G-5 emulsions in this stack were scanned along a line parallel to the top edge and 5 mm inside the stack. The scanning line had a length of about 5 cm. Tracks having a projected zenith angle $\theta\rho \leq 50°$, dip angle $\leq 29°$, and ionization ≥ 64 I_0 (the minimum of ionization), were accepted. These tracks were followed through the stack till they stopped, interacted or, left the stack.

The charge and energy of these nuclei were determined by a combination of δ-ray counting and range and scattering measurements. The general procedures adopted were discussed in previous literature in detail, Aizu et al.,

[1960]. Since, in the present work, the main emphasis is on the determination of the energy spectrum, not much attention is paid to resolving with care individual neighboring charges. We describe here briefly the methods adopted in the three cases.

(a) Stopping tracks — The charges of the tracks were identified by making δ-ray counts at the point where they crossed the scan line. Two δ-ray counting procedures were used: short δ-ray counting (in which δ-rays extending beyond a projected distance of $>3.2\mu$ from the track on either side were counted). At the end of the range an integral δ-ray count was performed over a distance of $\sim 2000\mu$ on favorable tracks that ended in G5 emulsions. These integral counts, for nuclei of different charges, are related by a "similarity law". [See Aizu et al., 1960] For calibration purposes, tracks having known charge values in emulsions exposed in previous rocket flights [Fichtel et al., 1965] and having the same ionization characteristics were used. The energy of each nucleus was estimated from the range and charge of the nucleus.

(b) Tracks leaving the stack or interacting — These were identified by counting short and long δ-rays (at least 200 in number) at the scan line and at a point close to the point of exit (1 cm from the exit) or interaction point. The calibration plot was derived from the well-identified long stopping tracks described in (a) above, and using the relation, the δ-ray density $N_\delta = a\left(\frac{Z^2}{\beta^2}\right) + b$ where a and b are constants and Z and βc are charge and velocity of the nucleus. The energy was estimated either for the change in the δ-ray density with range or from scattering measurements.

Each track was followed backwards to the edge of the stack and an energy spectrum of particles at the top of the stack was obtained.

The procedure adopted for extrapolating the observed spectrum to the top of the atmosphere was the same as that adopted by Aizu et al., [1960]. The effective mean vertical atmospheric depth is 2.4 g/cm^2; in view of the low value of the matter traversed, it is assumed here that all the fragmentation corresponding to 2.4 g/cm^2 of air occurs at the top of the atmosphere. Thus, the energy of each nucleus has been first corrected for ionization loss in air and then for loss due to fragmentation. The following parameters are used:

$$\lambda_{VH} = 12.9 \text{ g/cm}^2, \quad \lambda_H = 16.5 \text{ g/cm}^2, \quad P_{VHVH} = 0.28 \pm 0.28$$

$$P_{VH(SH)} = 0.33 \pm 0.15, \quad P_{SH(SH)} = 0.15 \pm 0.05 \; \{\text{VH: } Z \geq 20 \text{ and SH: } Z = 10 - 19\}$$

Results

Figure 1 shows the energy spectrum of the particles obtained at the top of the stack. The number of nuclei having a particular charge value is shown in the box corresponding to the energy interval. The differential intensities of H ($Z \geq 10$) nuclei obtained for the top of the atmosphere as a function of energy are given in Table 1 and are plotted in Figure 2. Also shown in this figure are the differential energy spectra of proton and helium nuclei obtained in this stack and at the same time by Fichtel et al. [1964]. The Mt. Washington neutron monitor counting rate on the day of the flight is 2148.

The energy spectra of P and α nuclei have been best studied for the year 1963 from the low energy region (~100 MeV/nucleon) to a few GeV/n (Balasubrahmanyan and McDonald [1965], Fichtel et al. [1965B], Frier and Waddington [1965], Ormes and Webber [1964]). The spectra thus obtained are also shown in Figure 2. The low energy rocket data as obtained by Fichtel et al. [1964] are combined with the satellite

TABLE 1

Differential intensities of heavy nuclei ($Z \geq 10$).

Kinetic energy (MeV/n)	Flux (dJ/dE) Particles/m^2 sec sv MeV.
160 - 275	0.0027 ± 0.0007
275 - 400	0.0035 ± 0.0008
400 - 600	0.0026 ± 0.0005
600 - 700	0.0019 ± 0.0006

data of Lim and Fukui [1965] to obtain an integrated energy spectrum of H-nuclei in the low energy region. The energy spectrum obtained by Koshiba et al. [1963] during a period close to solar maximum in a balloon flight (altitude ≈ 2 g/cm^2) is also shown in this figure. The neutron monitor data corresponding to the dates of the flight are indicated in the figure. It can be noted, from a comparison of the spectra as a function of time that (a) there is a decrease in intensity of nuclei as solar activity increases and (b) there is a shift of the maximum towards higher energy with increasing solar activity. There will be a further discussion of the experimental results in combination with the satellite and rocket data in the next section.

The helium spectrum has been measured in the present stack and is given in paper I. Similar simultaneous intensity measurements of α-particles and heavy nuclei were made by various authors (Aizu et al. [1960], Evans [1963], McDonald and Webber [1962], and Biswas [1965]). The values of $\Gamma_{H\alpha}$ computed from these measurements are given in Figure 3. It can be seen that the ratios do not change appreciably with time, thus indicating a charge independence of the modulation process in the energy region considered for the nuclei of same Z/A as has been predicted by various theoretical models.

Discussion

Source Spectrum

The integral flux values of cosmic ray nuclei determined for the highest possible known energy, from solar maximum to solar minimum, are near the equator, (Cutoff rigidity ~16GV); within the limits of experimental uncertainties and errors, these values do not show variation. Thus it is reasonable to assume that the flux values obtained for this energy represent those outside the solar system. The integral flux values of protons have been measured at energies $\sim 10^{12}$ eV, (See Webber [1964 B]), these flux values are shown in Figure 4.

The galactic cosmic ray spectra are normally represented as a power law either in total energy, W, the integral intensity, J_w (>W) of nuclei being given by $C_w W^{-\gamma}$, or in kinetic energy, E, the integral intensity J_e (>E) being given by $C_e E^{-\gamma}$ and in rigidity R, the integral intensity J_r (>R) being given by $C_r R^{-\gamma}$. The total energy, W, the kinetic energy, E, are expressed in GeV/n and rigidity R in GV, and C_w, C_e, and C_r are constants. The power law in total energy is predicated by various acceleration mechanisms. The statistical acceleration process proposed by Fermi [1954], the betatron mechanism of acceleration [Ginzburg and Syrovatsky, 1961], and the acceleration in hydromagnetic shock waves produced during supernova explosions [Colgate and Johnson, 1960] all lead to such an energy spectrum. Ginzburg and Syrovatsky [1961] have recently shown that, on the basis of general arguments concerning the equi-partition of energy in a turbulent magnetized plasma of cosmic dimensions, a power law in total energy of cosmic rays is a fundamental property of such a plasma.

A power law in kinetic energy has been used by Gloeckler, [1965] and Balasubrahmanyan et al. [1965] to explain the measured intensities of protons and helium nuclei by balloons and the IMP-I satellite; however, in their analyses they had to use a ratio of intensities of protons to helium nuclei $(P/\alpha) = 5.7$, which is much lower than the value obtained near the equator, where there is very little modulation. For this reason, a source spectrum which is a power law in kinetic energy is not considered in the present analysis.

The power law rigidity spectrum has recently been assumed by Kaplon and Skadron [1964]. There is, perhaps, no physical justification for assuming such a spectrum except for the fact that the solar flare spectrum could be represented by a rigidity spectrum. We assume in our analysis that the spectrum in the source regions is either (a) a power law in total energy, (herein referred to as source total energy spectrum) or (b) a power law in rigidity, R (herein referred to as source rigidity spectrum). We further assume that all the components, protons, α-particles and heavy nuclei have the same exponent, γ. This exponent is given as 1.35 from Figure 4. The values of constants C_W and C_r obtained for various nuclei are given in this figure. These values given here for protons may be compared with the values of $C_P = 5450 \pm 80$ and $\gamma_P = 1.43 \pm 0.10$ (or 1.31 as deduced by Waddington, [1960]) obtained by McDonald [1958] in the energy range 4-15 GeV/n from a comparison of the flux values measured at Texas and Guam.

Propagation in the Interstellar Medium

Various models, e.g., the regular model and the diffusion model, [Ginzburg and Syrovatsky, 1961] have been postulated for the diffusion of cosmic rays in interstellar space and a model of confinement of these nuclei in source regions has been given by Kaplon and Skadron [1964]; these models predict different variations of the path length with energy. We assume here the regular model of diffusion of cosmic rays in which all particles of a unique energy move along a definite path, for example, along the magnetic lines of force. We further assume that no acceleration takes place in the interstellar medium; the existing experimental evidence seems to indicate that a Fermi statistical acceleration mechanism cannot operate effectively in the interstellar medium [See, for example, Durgaprasad, 1965].

In Traversing a path length, X g/cm^2 of interstellar space, two competing processes occur, namely, the absorption of nuclei of the same species and the feeding-in of nuclei from heavier group through nuclear collisions and the loss of energy of particles due to ionization. For heavy nuclei of charge $Z \geq 10$, the energy loss and absorption of nuclei have been taken into account. Helium nuclei can arise from spallation of medium and heavy nuclei, besides being absorbed; however, the intensities of these nuclei are so low that to a first approximation, one could neglect the contribution from these nuclei. Consequently, the differential intensities of heavy nuclei ($Z \geq 10$) and alpha particles ($Z \geq 2$), (neglecting the contribution from the fragmentation of heavy nuclei and medium nuclei to alpha particles), can then be written as:

$$\left.\begin{aligned} \left(\frac{dJ}{dR}\right)_i &= \left(\frac{C_i}{R_i^{2.35}}\right)\left(\frac{DRSI}{DRSSI}\right) e^{-x/\Lambda_i} \\ \text{and} \quad \left(\frac{dJ}{dW}\right)_i &= \left(\frac{C_i}{W_i^{2.35}}\right)\left(\frac{DWSI}{DWSSI}\right) e^{-x/\Lambda_i} \end{aligned}\right\} \tag{1}$$

Where $(dJ/dR)_i$ and $(dJ/dW)_i$ are the intensities of differential rigidity and total energy of i-nuclei, R_i and W_i are the rigidity and total energy of i-nuclei, DRSSI, DWSSI are the rigidity and total energy intervals at the solar system for the corresponding intervals DRSI and DWSI at the source region, after traversal through X g/cm^2 of interstellar medium (for computing ionization loss, the medium is supposed to consist of neutral hydrogen) and Λ_i is the absorption mean free path of the i-nucleus. Using the values of C_i given in Figure 4 and the absorption mean free paths, ΛH = 6.0 g/cm^2, $\Lambda\alpha$ = 36.0 g/cm^2 and Λp = 72.0 g/cm^2, the unmodulated differential intensities of heavy nuclei and α-particles for energy and rigidity spectra at the vicinity of the solar system have been calculated for various values of X; from these values the ratios of intensities, $\Gamma_{H\alpha}$, were computed and are shown in Figure 3. The errors shown are derived from the errors on C_i. These are compared with the available experimental data on $\Gamma_{H\alpha}$ in the energy region, 200-700 MeV/n, (Figure 3). It can be seen from this comparison that a matter traversal of $\lesssim 2$ g/cm^2 for the source rigidity spectrum as well as for the source total energy spectrum is consistent with all the experimental data. This result is also in good agreement with the recent experimental evidence on the observed ratios of $He^3/(He^3+He^4)$ [Hildebrand et al., 1964] and of light L(Z = 3-5) to S-nuclei ($Z \geq 6$) [Hildebrand and Silberberg, 1964]. However, it is not in agreement with the observations that suggest an increase in the matter traversed with decreasing energy [e.g., Apparao, 1961 and Webber, 1965].

Propagation in the Solar System

The spectra thus obtained are modulated to a considerable extent by solar activity; different mechanisms have been postulated by means of which such changes can occur and, of these, two models seem to be currently in vogue; Parker's model and the electric field model. Recently Fichtel, Durgaprasad and Guss [1965B], from a study of the differential intensities of protons and α-particles, have shown that, assuming a similar spectra at the source, the generalized Parker's model can adequately represent the intensity variations during a solar cycle; however, the source spectra had peculiar shapes and could not be represented by a unique power law. Frier and Waddington [1965], on the other hand, assumed a total energy spectrum with an exponent of 1.5 and tried to show that an electric field model could be used to predict these intensity variations. We consider here both these models in great detail for the two kinds of spectra assumed, and discuss the significance of these parameters.

Electric field model: In this model it is assumed that the earth is at a positive potential and that positive particles do lose energy in traversal through the solar system; also they occupy a different volume in phase space, the density D in phase space being constant. Consequently, if P, M, and W are the momentum, mass, and total energy of these particles and J(P) and J(W) the corresponding differential intensities, the following relations hold good:

$$D = \frac{J(P)M}{P^3} = \frac{J(W)}{P^2} = \text{Constant} \tag{2}$$

Let us designate these intensities as being outside the solar system. Then the modulated intensities $g(P)'$ and $g(W)'$ could be obtained from:

$$\frac{g(P')M}{(P')^3} = \frac{J(P)M}{P^3} \quad \text{and} \quad \frac{g(W')M}{(W')^3} = \frac{J(W)M}{W^3} \tag{3}$$

Where the momentum P′ and total energy W′ of the particles after the modulation is related to the quantities P and W before modulation from the relation

$$W' = W + \frac{zev}{A} \tag{4}$$

Ze being the charge and V the positive electric potential of the earth with respect to infinity. Combining (1) and (3), we have the unmodulated intensity g(W) related to the source spectrum from the relation:

$$g(W) = \frac{dJ}{dE} = \left[\frac{W^2 - \left(m_0 c^2\right)^2}{(W+\Delta)^2 - \left(m_0 c^2\right)^2}\right] \frac{C_i}{\left(W_i + \Delta\right)^{2.35}} e^{-x/\Lambda_i} \left(\frac{DWSI}{DWSSI}\right) \tag{5}$$

[See, for example, Frier and Waddington, 1965] in the case of total energy spectra and

$$g(R) = \frac{dJ}{dR} = \left[\frac{W^2 - \left(m_0 c^2\right)^2}{(W+\Delta)^2 - \left(m_0 c^2\right)^2}\right]^{3/2} \frac{C_i}{R_i^{2.35}} e^{-x/\Lambda_i} \left(\frac{DRSI}{DRSSI}\right) \tag{6}$$

in the case of total rigidity spectra. Values of g(W) and g(R) have been calculated for different values of V and are compared to the flux values of protons and helium nuclei obtained for the year 1963 for a traversal of path lengths varying from 1 to 3 g/cm^2. These are given in Figure 5. From this figure it can be seen that a good fit to proton data of the year 1963 can be obtained using a value of V ~300 MV, but the agreement with helium nuclei data is not quite as good; this departure becomes more marked for the year 1961; a value of V = 500 MV can be fitted to the proton data but the measured intensity values of helium nuclei of the same potential for 1961 fall well below the calculated curve. In the case of source rigidity spectra, the proton data could be fitted using a value of V = 1000 MV whereas the helium nuclei data fall well below the line. Thus, besides the question concerning the existence of such high potentials of the order of a few hundreds of MV in the solar system, the experimental data could not be explained using this mode of modulation and the energy spectrum given above. We will now examine the applicability of the generalized Parker model to the present problem.

Parker's model: In this model, the differential intensity of particles in the vicinity of the earth, $g(i)$, is related to the unmodulated intensity, $J(i)$, in the vicinity of the solar system as [Parker, 1963]

$$g_i(i) = J(i) \exp\left(-\frac{3}{\beta}\int_{r_e}^{\infty} V/\lambda \, dr\right) \tag{7}$$

where i refers to the type of nucleus under consideration, V is the solar wind velocity, βc the particle velocity, r is the distance from the sun and λ is the scattering mean free path. By assuming that V/λ is independent of r from r_e to r_0 and zero thereafter, (7) can be written as

$$g(i) = J(i) \exp\left(-\frac{1}{\beta} D(R)\right) \text{ where } D(R) = \frac{3V\left(r_0 - r_e\right)}{\lambda(R)}$$

For λ, Parker [1956] suggested the form

$$\lambda = \text{Constant}\left[1 + \left(\frac{\pi\rho}{2L}\right)^2\right]$$

which is equivalent to

$$\frac{1}{\lambda} = \frac{\text{Constant}}{\left(1 + R^2/R_0^2\right)}$$

where ρ is the radius of curvature of the particle of rigidity R, L is the diameter of the scattering center, $R_0 = \frac{2BL}{\pi}$ and B is the magnetic field strength. Thus, (7) can be rewritten as

$$g(i) = J(i) \exp\left[- k/\beta \left(1 + R^2/R_0^2\right)\right] \tag{8}$$

k and R_0 being constants that depend on the solar wind velocity and the dimensions of the scattering centers.

Thus the observed intensity at the earth is related to the source spectrum from the relation,

$$\left(\frac{dJ}{dR}\right)_0 = \frac{C_i}{R_i^{2.35}} \left(\frac{DRSI}{DRSSI}\right) \exp\left[- k/\beta \left(1 + R^2/R_0^2\right)\right] e^{-x/\Lambda_i} \tag{9}$$

in the case of source rigidity spectrum, and from the relation

$$\left(\frac{dJ}{dE}\right)_0 = \frac{C_i}{W_i^{2.35}} \left(\frac{DWSI}{DWSSI}\right) \exp\left[- k/\beta \left(1 + R^2/ R_0^2\right)\right] e^{-x/\Lambda_i} \tag{10}$$

in the case of source total energy spectrum. For particles of a unique energy, there are three unknowns, namely K, R_0, and X; and the experimental intensities have been measured for three nuclei, namely protons, helium, and heavy nuclei. The measured intensities of $(dJ/dR)_0$ and $(dJ/dE)_0$ for the years 1963 and 1961 are given in Figure 6 (a) and (b) respectively and these fluxes have been fitted for various values of K and R_0 as shown in these figures.

It can be seen that a reasonable fit to the experimental points can be obtained in the case of source rigidity spectrum for values of $k = 2.1$ and $R_0 = 1.6$ for the year 1963 and for values of $k = 2.2$ and $R_0 = 2.0$ for the year 1961. A similar attempt has been made in the case of total energy spectra; the agreement is not so good as can be seen from the figure. The values of k and R_0 obtained here are of the order of magnitude that one would expect from the known solar wind velocities and expected sizes of magnetic irregularities [Parker, 1963]. Thus one can conclude that the modulation mechanism described by Parker's model and a source rigidity (or a total energy) spectrum would adequately predict the intensity variations with solar activity; the matter traversed at low energies being ~ 2 g/cm^2. This value should be compared to a value of 2.5 g/cm^2 of hydrogen used for nuclei of relativistic energies; thus, the value is either constant or else it decreases with decreasing energy.

A slight decrease in the matter traversed by the radiation with decreasing energy is not quite unexpected, for if the low energy and high energy particles are produced at the same time, have the same age t (this is true if the bulk of cosmic ray nuclei of all energies are produced at the same time in the past, e.g., in a violent explosion of the nucleus of our galaxy or some other), and traverse regions of similar density (n), then from the simple relation, $X = \beta c\, nt$ where βc is the velocity of the particle, one could infer that low energy particles traverse less matter than the high energy ones. This assumes a simple diffusion process and the energy or the rigidity spectrum that is observed in cosmic rays could be mainly dominated by such a diffusion process in the source regions and in interstellar space. The solar cosmic ray events do show a rigidity dependent spectrum [e.g., Webber, 1964] and it is reasonable to expect a similar situation to occur in the galactic or extragalactic cosmic rays as well. Further studies of the energy spectrum and the intensity of the low energy cosmic ray particles using space vehicles would likely reveal some interesting information on the diffusion of particles in space and on the source spectrum of these nuclei.

Acknowledgments: I am grateful to Dr. L. Meredith and Dr. Frank B. McDonald for encouragement in carrying out this work. I also wish to thank Drs. C. E. Fichtel, E. Boldt and V. K. Balasubrahmanyan for discussions. I also wish to thank the National Academy of Sciences for offering me the Resident Research Associateship.

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Figure Captions

Figure 1: Energy spectrum of heavy nuclei ($Z \geq 10$) observed at the top of the stack. The numbers indicated in the box refer to the measured charge of the nucleus.

Figure 2: Differential intensities of protons, helium, and heavy nuclei measured in 1963, 1961 and 1959 as a function of kinetic energy (MeV/nucleon) and rigidity. The numbers in brackets refer to the counting rate of the Mt. Washington neutron monitor.

Figure 3: Ratios of intensities of heavy nuclei to alpha particles plotted as a function of Mt. Washington neutron monitor rate. Also shown in the text are the ratios predicted from Equation (1) (See text). The data shown refer to: A: Aizu et al. [1960]. P: present work. M: McDonald and Webber [1962], E. Evans [1963] and B. Biswas [1965].

Figure 4: Integral intensities of protons plotted as a function of kinetic energy (and rigidity) for $E \gtrsim 15$ GeV where the effects of solar modulation are assumed to be negligible. The constants C_p, C_α and C_H are those that define the integral intensities at the source (see text). The data shown are derived from Webber's review article (Webber, 1964B).

Figure 5(a): Differential spectrums of protons and helium nuclei measured in 1963 plotted as a function of magnetic rigidity. The curves show predicted spectra for modulating potentials of 900 and 1000 MV, and for different values of interstellar matter traversed (given in brackets).

Figure 5(b): Differential intensities of protons and helium nuclei measured in 1961 and 1963. The curves show predicted spectra for modulating potentials of 200, 300, 500 and 700 MV (see text: electric field model) and for different values of interstellar matter traversed (given in brackets).

Figure 6: Differential spectra of protons, helium and heavy nuclei measured in 1963 and 1961 plotted as a function of (a) magnetic rigidity (MV) and (b) kinetic energy MeV/n. The curves shown refer to various values of K and R_0 (see text: Parker's model) and X; the interstellar matter traversed as indicated in the figure.

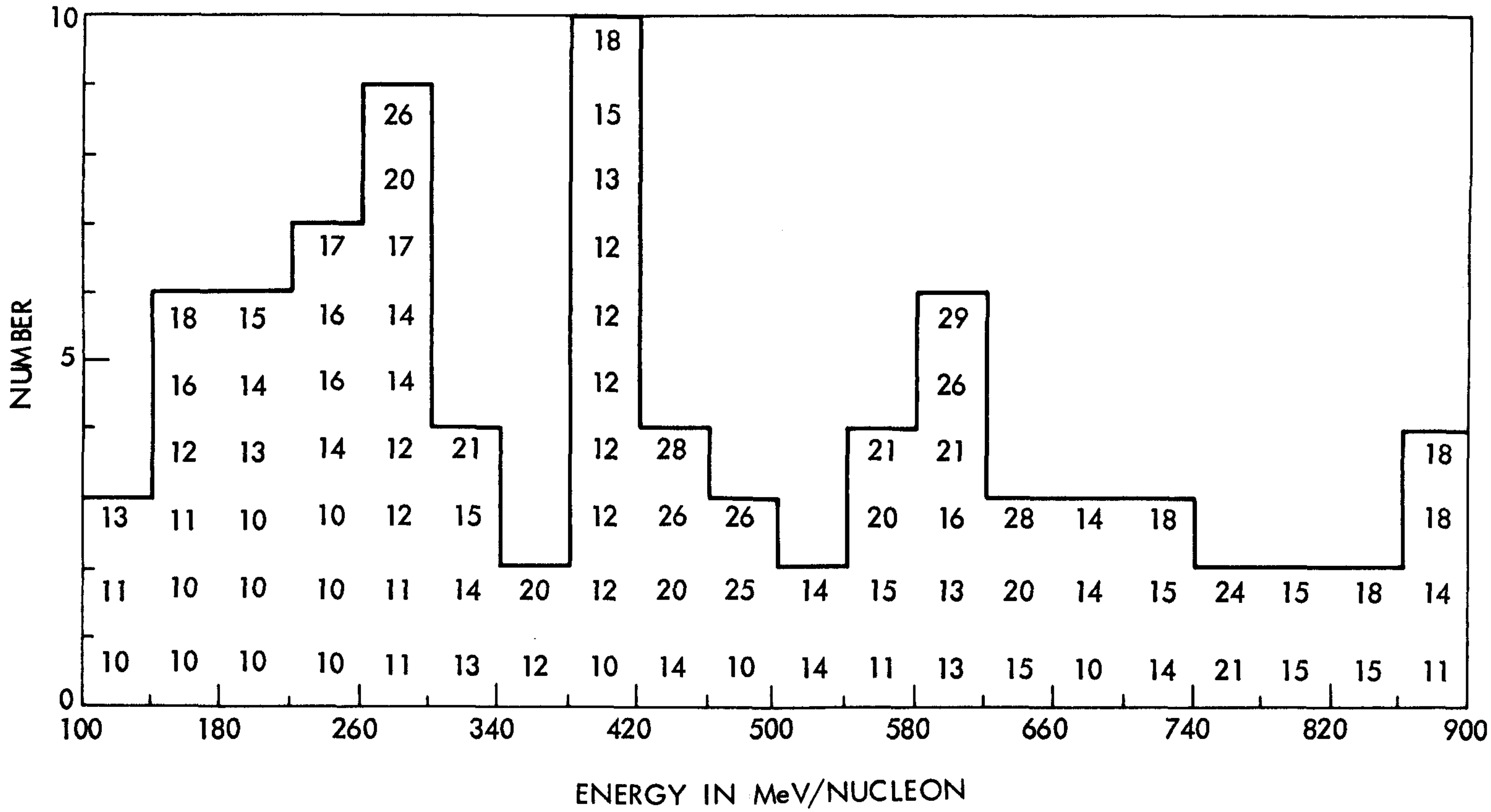

NUMBER
0
5
10
100
180
260
340
420
500
580
660
740
820
900
ENERGY IN MeV/NUCLEON

FIGURE 1

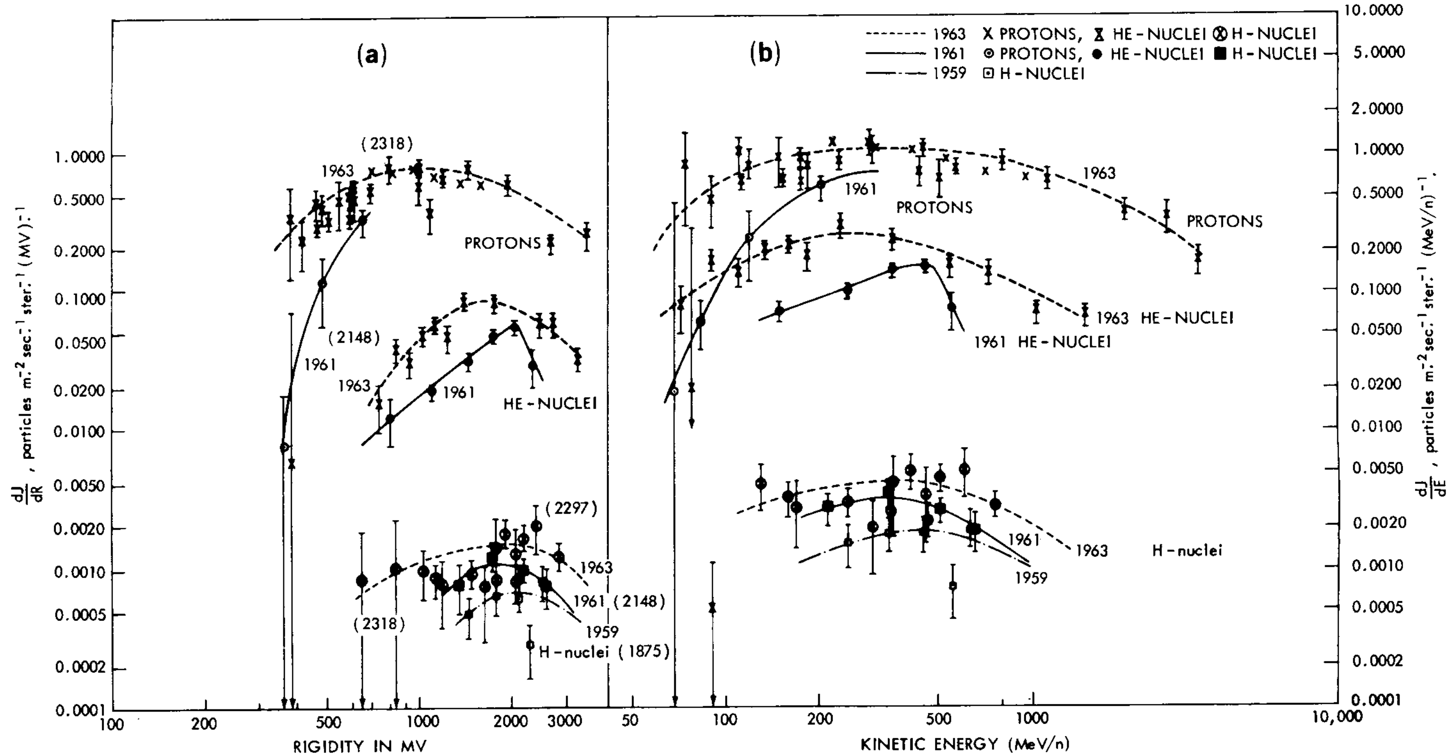

(a)
(b)
1963 X PROTONS, HE-NUCLEI H-NUCLEI
1961 PROTONS, HE-NUCLEI H-NUCLEI
1959 H-NUCLEI
(2318)
1963
PROTONS
(2148)
1961
HE-NUCLEI
(2297)
1961 (2148)
1959
H-nuclei (1875)
PROTONS
HE-NUCLEI
H-nuclei
RIGIDITY IN MV
KINETIC ENERGY (MeV/n)
dJ/dR, particles m.$^{-2}$ sec.$^{-1}$ ster.$^{-1}$ (MV)$^{-1}$
dJ/dE, particles m.$^{-2}$ sec.$^{-1}$ ster.$^{-1}$ (MeV/n)$^{-1}$

FIGURE 2

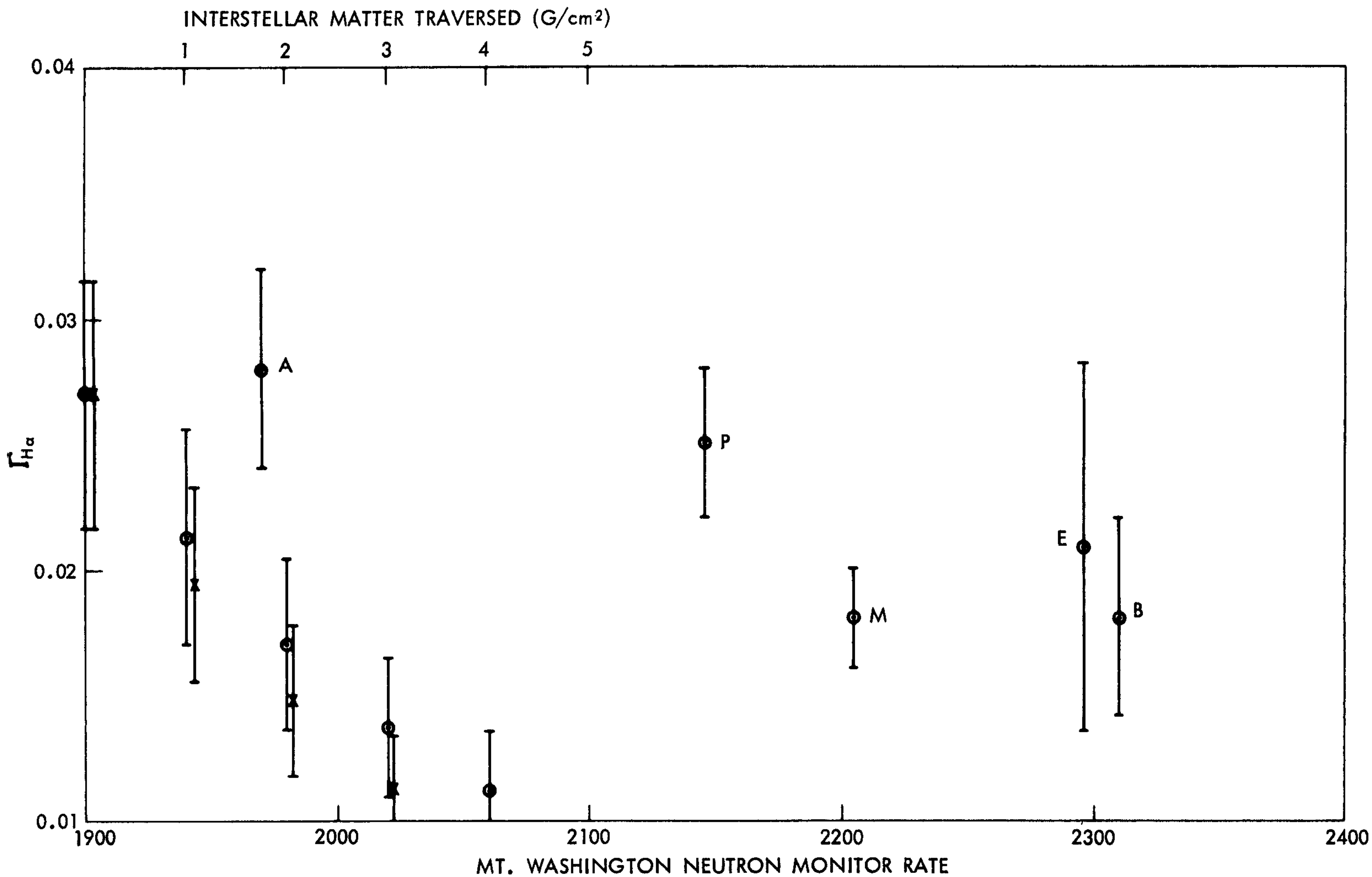
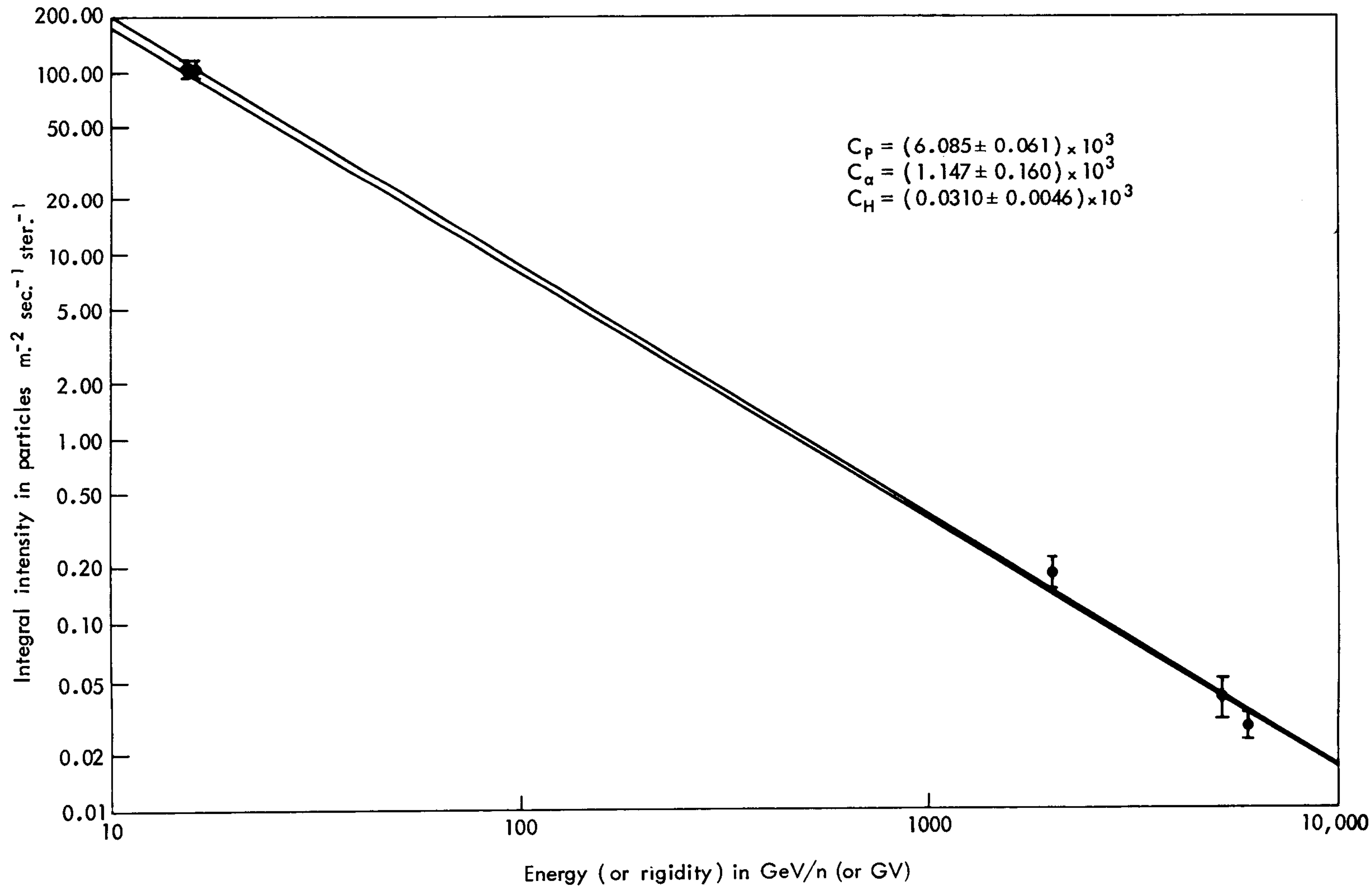

INTERSTELLAR MATTER TRAVERSED (G/cm²)
1
2
3
4
5
0.04
0.03
0.02
0.01
$\Gamma_{H\alpha}$
A
P
E
M
B
1900
2000
2100
2200
2300
2400
MT. WASHINGTON NEUTRON MONITOR RATE

FIGURE 3



200.00
100.00
50.00
20.00
10.00
5.00
2.00
1.00
0.50
0.20
0.10
0.05
0.02
0.01
Integral intensity in particles m.$^{-2}$ sec.$^{-1}$ ster.$^{-1}$
10
100
1000
10,000
Energy (or rigidity) in GeV/n (or GV)
$C_P = (6.085 \pm 0.061) \times 10^3$
$C_\alpha = (1.147 \pm 0.160) \times 10^3$
$C_H = (0.0310 \pm 0.0046) \times 10^3$

FIGURE 4

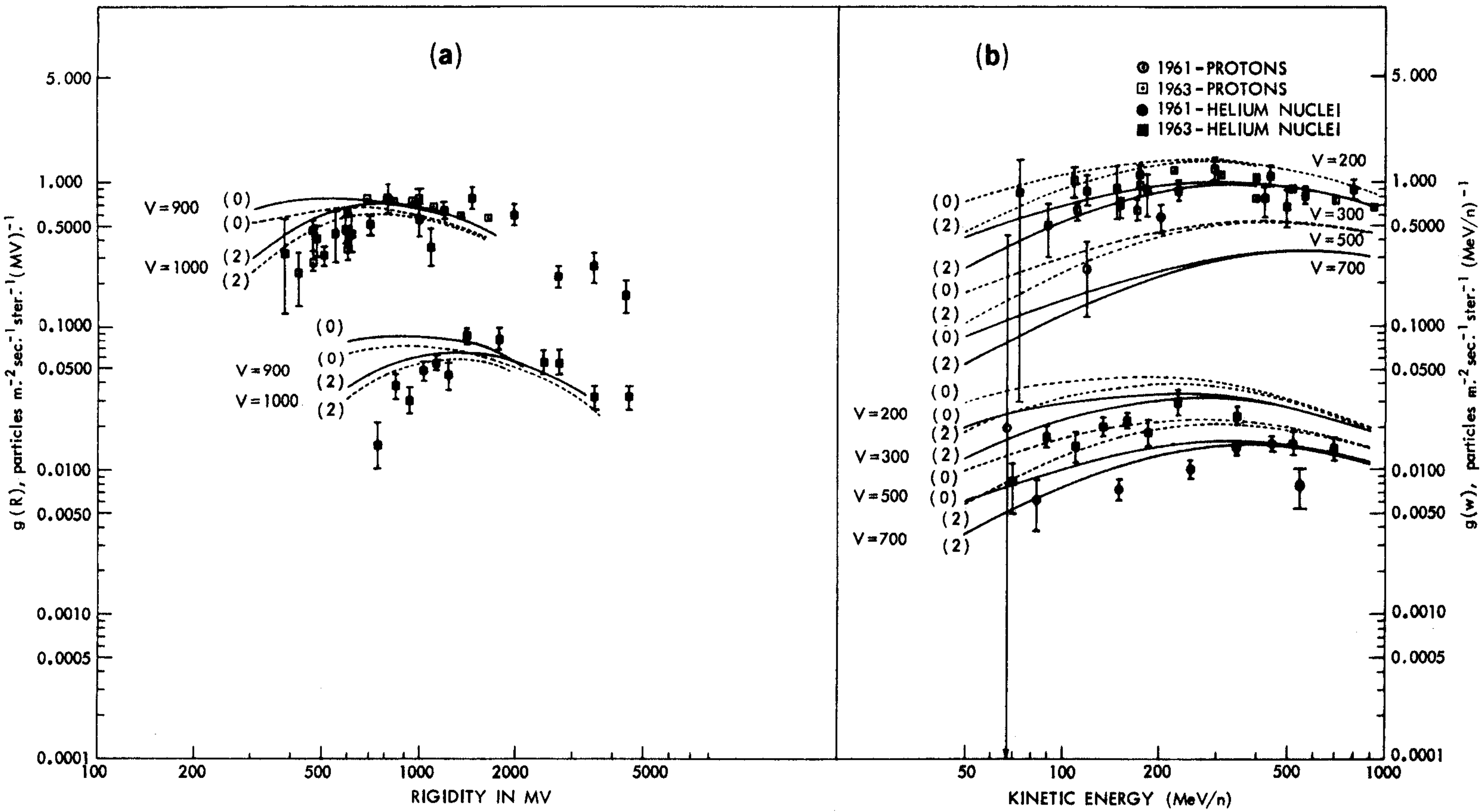

(a)
(b)
1961 - PROTONS
1963 - PROTONS
1961 - HELIUM NUCLEI
1963 - HELIUM NUCLEI
V = 900
V = 1000
V = 200
V = 300
V = 500
V = 700
(0)
(2)
g (R), particles m.$^{-2}$ sec.$^{-1}$ ster.$^{-1}$ (MV)$^{-1}$
g (w), particles m.$^{-2}$ sec.$^{-1}$ ster.$^{-1}$ (MeV/n)$^{-1}$
RIGIDITY IN MV
KINETIC ENERGY (MeV/n)
5.000
1.000
0.5000
0.1000
0.0500
0.0100
0.0050
0.0010
0.0005
0.0001
100
200
500
1000
2000
5000
50

FIGURE 5

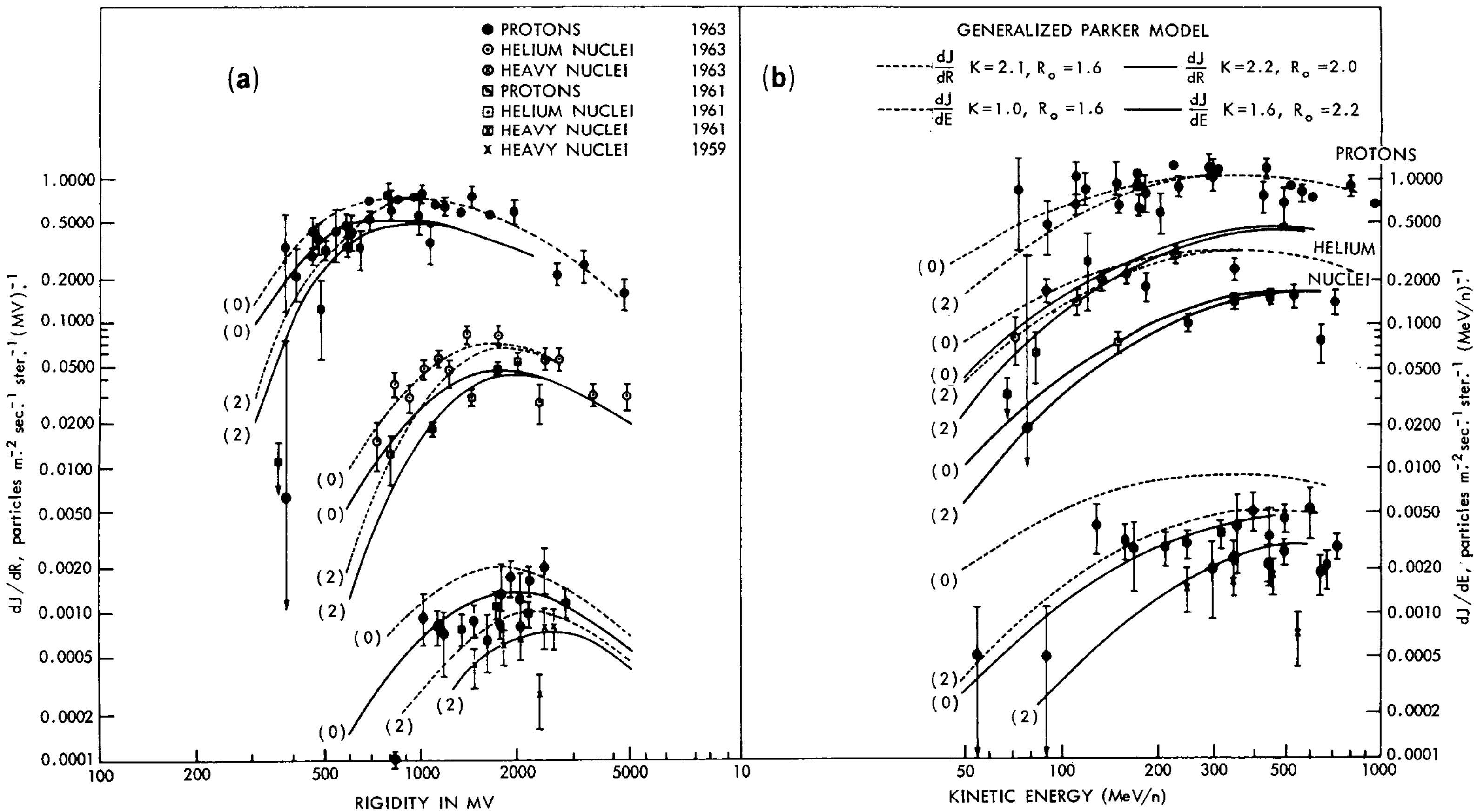

(a)
● PROTONS 1963
⊙ HELIUM NUCLEI 1963
⊗ HEAVY NUCLEI 1963
PROTONS 1961
HELIUM NUCLEI 1961
HEAVY NUCLEI 1961
x HEAVY NUCLEI 1959
(b)
GENERALIZED PARKER MODEL
dJ/dR K=2.1, Ro=1.6
dJ/dR K=2.2, Ro=2.0
dJ/dE K=1.0, Ro=1.6
dJ/dE K=1.6, Ro=2.2
PROTONS
HELIUM NUCLEI
dJ/dR, particles m.^-2 sec.^-1 ster.^-1 (MV)^-1
dJ/dE, particles m.^-2 sec.^-1 ster.^-1 (MeV/n)^-1
RIGIDITY IN MV
KINETIC ENERGY (MeV/n)

FIGURE 6