Pergamon

Adv. Space Res. Vol. 14, No. 10, pp. (10)749–(10)757, 1994
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0273–1177/94 $7.00 + 0.00

LONG-TERM MODULATION OF GALACTIC COSMIC RADIATION AND ITS MODEL FOR SPACE EXPLORATION

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ABSTRACT

As the human exploration of space has received new attention in the United States, studies find that exposure to space radiation could adversely impact the mission design. Galactic Cosmic Radiation (GCR), with its very wide range of charges and energies, is particularly important for a mission to Mars, because it imposes a stiff mass penalty for spacecraft shielding. Dose equivalent versus shielding thickness calculations, show a rapid initial drop in exposure with thickness, but an asymptotic behavior at a higher shielding thickness. Uncertainties in the radiobiology are largely unknown. For a fixed radiation risk, this leads to large uncertainties in shielding thickness for small uncertainties in estimated dose. In this paper we investigate the application of steady-state, spherically-symmetric diffusion-convection theory of solar modulation to individual measurements of differential energy spectra from 1954 to 1989 in order to estimate the diffusion coefficient, $\kappa(r,t)$, as a function of time. We have correlated the diffusion coefficient to the Climax neutron monitor rates and show that, if the diffusion coefficient can be separated into independent functions of space and time: $\kappa(r,t)=K(t)\kappa_0\beta P\kappa_1(r)$, where β is the particle velocity and P the rigidity, then (i) The time dependent quantity $1/K(t)$, which is proportional to the deceleration potential, $\phi(r,t)$, is linearly related to the Climax neutron monitor counting rate. (ii) The coefficients obtained from hydrogen or helium intensity measurements are the same. (iii) There are different correlation functions for odd and even solar cycles. (iv) The correlation function for the Climax neutron monitor counting rate for given time, t, can be used to estimate mean deceleration parameter $\phi(t)$ to within $\pm$ 15% with 90% confidence. We have shown that $\kappa(r,t)$ determined from hydrogen and/or helium data, can be used to fit the oxygen and iron differential energy spectra with a root mean square error of about $\pm$ 10%, and essentially independent of the particle charge or energy. We have also examined the ion chamber and ^{14}C measurements which allow the analysis to be extended from the year 1906 to 1990. Using this model we have defined reference GCR spectra at solar minimum and solar maximum. These can be used for space exploration studies and provide a quantitative estimate of the error in dose due to changes in GCR intensities.

INTRODUCTION

The radiation exposure from galactic cosmic radiation will pose a particularly serious hazard for long duration interplanetary missions. In designing the required shielding for the spacecraft one should consider the *worst case* GCR intensities and the implications of their uncertainties. These worst case intensities should be based on the long-term record of cosmic ray measurements. Reliable measurements of GCR intensities began to be made soon after the discovery of heavy, charged-particles in 1948. There are three components to estimate of mission doses: (i) the GCR intensities (ii) their transport through shielding matter, and (iii) a means of converting physical doses to biological risk. The radiation quality factor is widely used for this purpose. This factor is based on the collective judgement of a group of experts, as such, no errors are assigned to it. Based on this definition, radiation exposure are formulated for a given risk. Thus, the exposure limits and the quality factor are coupled quantities. Recently, estimates of the radiation dose have been calculated as a function of shielding thickness/1,2,3,4/ using the ICRP-26/5/ and ICRP-60/6/ definitions of the quality factors. Adams *et al.*/7/ developed the Cosmic Ray Effects on Micro-Electronics (CREME) model to predict single event upset rates from radiation exposure. This model was based on a systematic study of the GCR intensities between 1965 and 1980. It has been the most widely used model of GCR intensities for dose calculations in the last few years. However, a number of very high resolution measurements of GCR intensities, with excellent counting statistics, have been reported since 1980. Since then it has also been recognized that the solar modulation of GCR intensities has approximately a 22 years cycle instead of the 11-year cycle used in the model. This weakness of the model was recognized from the time of its introduction.

In this paper we discuss the development of a GCR model that is based on the conventional diffusion-convection theory of solar modulation. It includes a systematic study of all of the available measurements obtained from 1954 to 1989, a period of nearly two 22-year cycles.

SOLAR MODULATION EFFECTS

It is now well established that the energy spectra of all GCR nuclei at very high energies is a power-law function of kinetic energy per nucleon. However, indices of the power law are different for different nuclei, and that secondary nuclei have a steeper slope than primary nuclei. The differential energy spectra have a maximum value between 300 and 500 MeV/n , and monotonically decreases down to about 10 MeV/n. At 1 A.U. the low energy part of the spectra (< 5 GeV/n) is affected by solar activity.

The basis of the solar modulation theory/8,9/ is the Fokker-Planck equation of the modulated number density U(r,E) per unit kinetic energy per nucleon. The basic equation is:

$$\frac{\delta U}{\delta t} = \nabla(\kappa_s \times \nabla U) - \left(\vec{V}_{sw} + \vec{V}_d\right)\nabla U + \frac{1}{3}\nabla \times \vec{V}\frac{d(\alpha EU)}{dE} = 0 \quad (1)$$

Here r is the heliocentric radius and E the kinetic energy/nucleon, $\vec{V}_{sw}$ is the vector solar wind velocity, κ_s is the symmetric part of the diffusion tensor, $\vec{V}_d$ is the velocity resulting from particle gradient and the curvature in the nonuniform interplanetary magnetic field and is related to the anti-symmetric part of the diffusion tensor, κ_a, $\alpha = (E+2m_p)/(E+m_p)$, and m_p is the proton rest mass/10,11,12/. If the heliosphere is assumed to be spherically symmetric,and the cosmic ray intensities isotropic, then the model has three free parameters: the diffusion coefficient, κ, the solar wind velocity, V_{sw}, and the radius of the heliosphere, r_B. Urch and Gleeson/13/ showed that full numerical solutions of the equation are well represented by the deceleration parameter

$$\phi(r,t) = \frac{1}{3}\int_r^{r_B} \frac{V_{sw}(r',t)}{\kappa(r',t)}\,dr' \quad (2)$$

and the intensity, $J(r_1,E,t)$ at point r_1 is related to the intensity at point r_2 by

$$J_2(r_2,E,t) = J_1(r_1,E,t) \quad \exp\left[\phi(r_2,t) - \phi(r_1,t)\right] \quad (3)$$

If the $\kappa(r,t)$ and $V_{sw}(r,t)$ are assumed to be separable in r and time, then $\phi(r,t) \equiv F(r)/F(t)$. In a number of other investigations κ is taken to be of the form $\kappa(t)\kappa_0\beta\kappa_1(r)\kappa_2(P)$ where the function $\kappa_2(P)$ contains the rigidity dependence of the parallel component of the diffusion coefficient. Garcia-Munoz *et al.*/14/ and Webber *et al.*/15/ assumed that $\kappa = K(t)\kappa_0\beta P^\delta$ where $\delta = 0$ for $P_c > 0.3$ GV, and $\delta = 1$ for $P_c > 0.3$ GV. Webber *et al.*/15/ took the break point, P_c, to be 0.4 GV. With this form of κ, Lezniak and Webber/16/ showed that in the force-field approximation, the intensity J(r,E) is:

$$J(r,E) = e^{-2^{\lambda}} J(r_B, E\, e^{\lambda}) \quad (4)$$

where $\lambda = \phi/P_c$. This means that the form of the interstellar spectrum, $J(r_B,E)$ is preserved, but shifted in energy and magnitude. In our earlier paper/17/, we examined the power law form of the diffusion coefficient and concluded that it is not necessary to introduce a break-point rigidity, and that the 'best' fits of the differential energy spectra were obtained for δ=1. Three-dimensional drift models of GCR modulation/18/ predict modulated intensities that are relatively insensitive to the solar wind velocity, diffusion coefficient, and the size of the modulating region. Instead, changes in the large scale general structure of the magnetic field that are associated with the flare activity and the field polarity play the most significant part in the modulation of GCR intensity. Thus, in an equilibrium heliosphere, a single parameter, ϕ, can define the modulated intensities. It should be noted that in case of separable κ, an approximation to the full numerical solution that is valid for energies above about 200 MeV/n can be given by/13/:

$$\frac{J(r,E)}{E^2 - m_p^2} = \frac{J(r_B, E+\Phi)}{(E+\Phi)^2 - m_p^2} \quad (5)$$

where Φ, the *potential energy*, is related to ϕ by $\Phi(r,t) = Ze\phi(r,t)$, Ze is the particle charge. This conventional model of GCR modulation has received wide acceptance and has been used by Evenson *et al.*/20/, Garcia-Munoz *et al.*/14/, and Webber and Yushak/21/. In this paper we have applied the conventional diffusion-convection theory of solar modulation to the differential energy spectral data from 1954 to 1989. We have numerically solved the radial part of the Fokker-Planck equation (1) using the technique of Fisk/19/ and estimated the K(t) part of the diffusion coefficient (κ_0 at 1 A.U. is taken to be 1.507×10^{22} cm^2/sec GV). We assumed a fixed solar wind velocity of 400 km/sec and the heliospheric boundary at 50 A.U. We have also assumed that the radial part of the diffusion coefficient, $\kappa_1(r)$, is a constant.

INTERSTELLAR SPECTRA

The solution of the Fokker-Planck equation is not unique. It clearly depends on the choice of the local interstellar spectra, LIS. The choice of possible LIS has narrowed considerably as our knowledge of both the modulation and intensity measurements have increased . Measurements from *Pioneer 10 and Voyager I and 2* at 42.5 AU have greatly limited the possible interstellar spectra of protons and helium nuclei. The LIS have been given by Evenson *et al.*/20/, and more recently by Webber/22,23/. Badhwar and O'Neill/17/ using these as a starting point, determined a new set for protons, helium, oxygen, and iron. Figure 1 shows these spectra and their comparison to some other estimates. Our proton and helium LIS differ significantly from those of Evenson *et al.*/20/ and Webber/22/ for energies below about 300 MeV/n, whereas the iron LIS also differs significantly from those given by Tang/24/ and Webber and Yushak/21/ at all energies. Our proton and helium spectra are consistent with data from *Pioneer 10 and Voyager I and 2*. At very low energies the anomalous component leads to higher intensities than our LI spectra. Thus, in modulation studies we restricted the particle energy to greater than 50 MeV/n to minimize the contribution of the anomalous component.

DATA SET AND PERIOD OF DATA ACQUISITION

We searched the available published literature for measurements of the differential energy (or rigidity) spectra of protons, helium, oxygen, and iron nuclei between 1954 to 1989. A critical review of these data sets is not possible here. Much of the data from solar cycle 19 came from the work of Freier *et al.*/25/ and McDonald and Webber/26,27/. These measurements of helium nuclei were made from balloon flights. We have adjusted their flux values slightly due to the revision of the absorption mean free path. There is a very large data set for cycles 20 and 21, and most of them are listed under reference 28. During most of cycle 20, no iron intensity measurements were made. Therefore, we have derived the iron spectra by converting the measurements of the VH-group (very heavy) of ions using the best measurements available for the Fe/VH ratio as a function of kinetic energy per nucleon. Using measurements of the oxygen and Fe with good statistics from about 600 MeV/n to about 35 GeV/n/29/, and on iron/30/, we have defined the high energy part of the spectra of oxygen and iron accurately. Similarly, flights of a magnetspectrometer/31/ have provided measurements with high statistics for hydrogen and helium. However, systematic errors of 10-15% may still be present. Interested readers can see a critical review on iron measurements up to 1977 in reference 21. There are also numerous review articles/32/. Measurements from the current cycle 22 continue to be obtained, but only limited published data sets are available. However, we have used all of these measurements. Recent measurements show that the ^{3}He/^{4}He ratio varies significantly as a function of the energy per nucleon/33/. We have neglected this dependence as well as the isotopic composition of other nuclei.

ANALYSIS

Figure 2 shows fits of the helium measurements for several years using the helium LIS described above. The data fits are quite good throughout the range from solar minimum to solar maximum, except for the anomalous component. There is a monotonic change in the estimated value of K(t) with solar activity. Figure 3 shows fits to hydrogen, helium, oxygen, and iron for the 1976-77 time period. This time period was characterized by the deepest solar minimum in the last 40 years. The fits for 1976-77 were made using the helium and hydrogen measurements. The same value of K derived from hydrogen and helium data was applied to the oxygen and iron data produces good fits for all four nuclei. It should be noted out that the oxygen data actually covers a broad time range from 1974-77. The value of κ estimated here is in good agreement with the analysis of Evenson *et al.*/20/, and Garcia-Munoz *et al.*/34/. Figure 4 shows a similar plot for 1973, a time near solar maximum. These data also are fit well. Thus, the conventional diffusion-convection theory provides an adequate description of the modulation of the nucleonic component of GCR. Using this approach, we have fitted all of the available hydrogen and helium data from 1954 to 1989. Figure 5 shows a cross plot of the $K_H(t)$ and $K_{He}(t)$ from these data sets where both the hydrogen and helium measurements were available. One sigma error estimates of the estimated K are shown. The solid line is a weighted least squares fit, taking errors in both direction into account. The equation of the

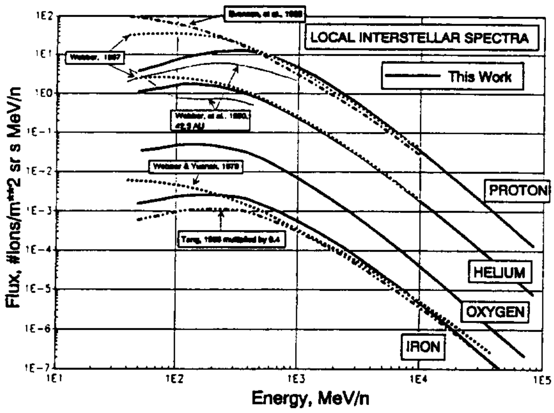

Fig. 1. Derived local interstellar spectra of hydrogen, helium, oxygen, and iron.

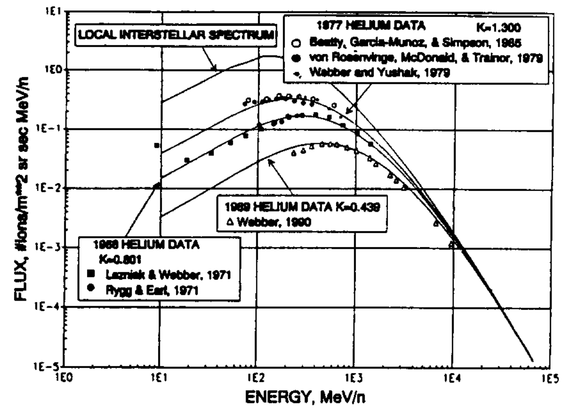

Fig. 2. A plot of the helium differential energy spectra and the corresponding fits to the diffusion theory.

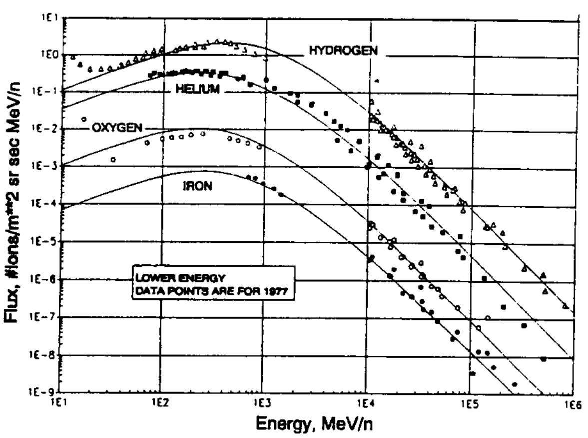

Fig. 3. A plot of the 1976-77 solar minimum spectra of hydrogen, helium, oxygen, and iron and fits to the diffusion theory with the same K value.

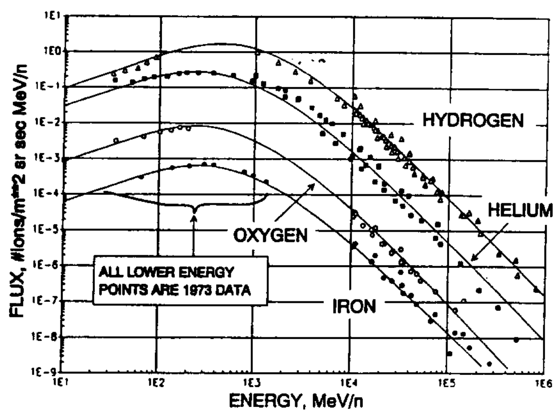

Fig. 4. A plot of the 1973 solar maximum spectra of hydrogen, helium, oxygen, and iron and fits to the diffusion theory with the same K value.

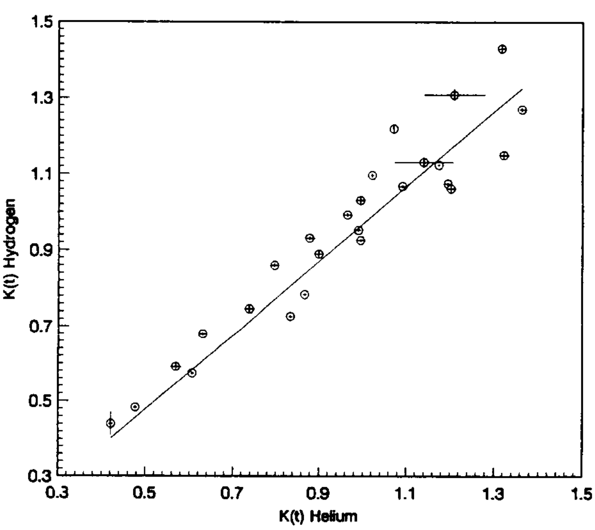

Fig. 5. A cross plot of derived K from hydrogen and helium data.

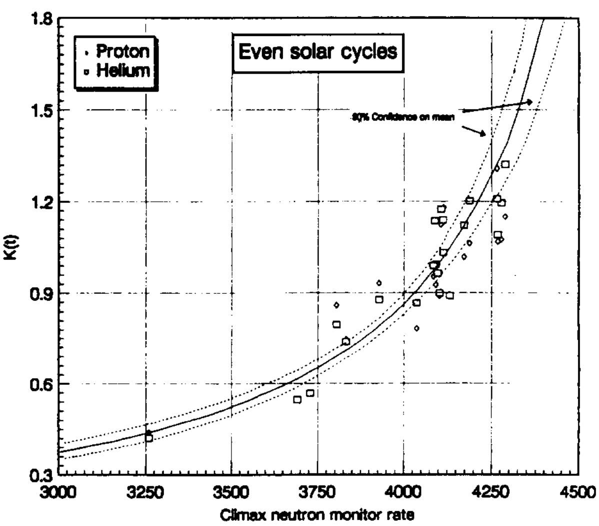

Fig. 6a. A plot of K versus the Climax neutron monitor rate for even cycles.

weighted least square line is: $K_H = (-0.0125 \pm 0.0496) + (0.982 \pm 0.0517)\ K_{He}$ with R-square of 0.94. Thus, proton and helium K-values correlate well and, the K values can be derived from either nuclei as well.

In our earlier paper/ 17/ we showed that this model leads to a root mean square error of about 9.8% in the absolute intensity of iron nuclei. That analysis showed that the error is essentially independent of the particle energy. An analysis of the hydrogen, helium, and oxygen shows similar results.

In order to determine whether this technique can provide a capability for predicting the level of solar modulation, we have attempted to correlate the Climax neutron monitor rate (cut-off rigidity, P_c=3 GV, effective rigidity of ≈ 5 GV) to the estimated values of K. In our earlier paper, the estimates of K were obtained without regard to the time of the year in which the measurements were made . It was *assumed* that K is linearly correlated to the yearly averaged Mt. Washington neutron monitor rate. This, however, leads to unphysical values of K, if the correlation function was applied to daily neutron monitor rate from 1989. Figure 6(a) and 6(b) show a plot of K(t) versus the Climax neutron monitor rate on the day of the GCR measurements, and for even and odd solar cycles, respectively. The solid lines are least square fits to the data. The dashed are the 90% confidence limit lines on the *mean* K. The equations for the least squares fits are: $(1/K)_{Odd} = (7.5896 \pm 0.5809) - (1.61845 \pm 0.1415) \times 10^{-3}$ Climax Rate, and $(1/K)_{Even} = (6.5077 \pm 0.5367) - (1.3421 \pm 0.1308) \times 10^{-3}$ Climax Rate. The R-squares values are 0.862 and 0.840, respectively. These data show that the mean value of K can be derived within ± 15% with 90% confidence from the Climax neutron monitor rate. Recall that 1/K is proportional to the deceleration parameter, ϕ. Thus the uncertainty in the estimate of ϕ is about the same. Figure 7 shows estimates of K obtained by fitting the differential energy measurements as a function of the time. The solid line is the estimated K value using the regression equations above and the Climax neutron monitor rate. The 1954 and 1977 minima were approximately the same, as were the 1959 and 1983 maxima. There are, however, some significant differences that we now discuss.

Figure 7 indicates a lag of several months to a year between the K-value and neutron monitor rate. The lag depends on solar activity, and is shorter during the decreasing phase of the solar cycle. These results are consistent with those of Simpson/35/ who also found that the lag decreases with increasing rigidity. O'Gallagher/36/ suggested that the lag, τ, has two characteristic times, the time, τ_V, required for the solar wind to carry the information on polarity reversal from the solar surface to the modulation boundary, and the time, τ_D, required for the cosmic rays to recognize the reversal and by diffusion or convection to reach the earth, that is, $\tau = (\tau_D^{-2} + r_V^{-2})^{-1/2}$, where $\tau_D = r_{2B}/6\kappa$ and $\tau_V = r_B/V_{SW}$. This model provides a reasonable explanation of the time lag within the framework of conventional diffusion-convection modulation theory.

In this approach the radial gradient of the GCR is zero, which is inconsistent with observations. However, if intensity variations along a trajectory in free space are desired, the radiation dependence can be easily introduced. The radial dependence of the diffusion coefficient can be taken from the work of Fulks/37/ to be of the form $\kappa_1(r) \propto \exp([r-1]/33)$, where r is in units of A.U. This form is consistent with that given by Nagashima and Morishita/38/, and extensively used by Garcia-Munoz *et al.*/34/.

LONGER TERM MODULATION

The long-term behavior of variation in the cosmic ray intensity can be studied by using measurements obtained with ion chambers in the atmosphere, and from ^{14}C measurements. A number of studies/39/ have shown that the ion chamber counting rates in the stratosphere are highly correlated with the neutron monitor rate at various geographic locations. Thus, ion chamber data can be used in the place of neutron monitor rate in years prior to their measurements. Data on the cosmic ray intensities from ion chambers at Huancayo, Peru (P_c ≈ 13 GV), corrected for barometric pressure and instrumental drifts, from June 1936 to Dec 1957 are given by Forbush/40/, from 1954 to 1976 by Cooper and Simpson/41/, and from 1976 to 1987 by Poielawska and Simpson/42/. Nagashima and Morishita/38/ showed that in the overlapping time periods the Huancayo ionchamber and Deep River neutron monitor rate have a correlation coefficient of 0.97. Thus, the Huancayo, Peru data provide a continuous record of cosmic ray intensity variation from 1936 and the present. Shea/43/ pointed out that cosmic ray measurements at western hemisphere latitudes only have to be adjusted for long-term drift in the geomagnetic cutoff. The correction increases the counting rate by about 0.12% per year/42/. Figure 8 shows the intensity variation from June 1936 to the present as indicated for the Climax neutron monitor rate, where the ion chamber data has been normalized using data from the overlapping time periods. Using the correlation of K(t) versus Climax data obtained from GCR spectral measurements, this intensity variation can be converted to the diffusion coefficients. These results indicate that the largest value of K is 1.5, consistent with weekly measurements from the 1976-77 period made by Evenson *et al.*/20/ and they are also consistent with our results. The lowest value of K is around 0.3; however, if K is averaged over a period of a few months, the lowest value is around 0.4.

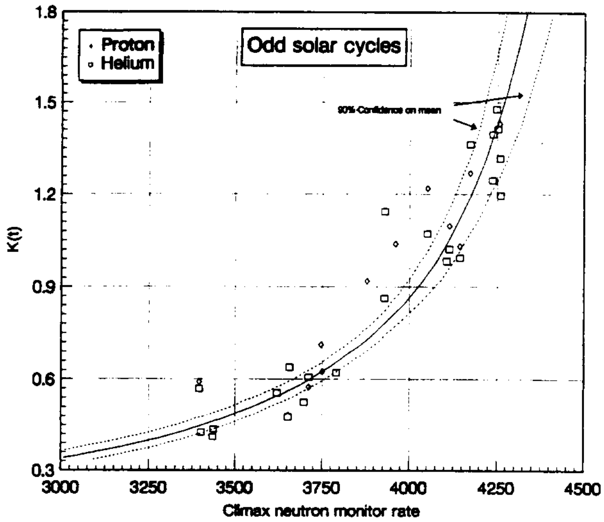

Fig. 6b. Same as 6(a) but for odd cycles.

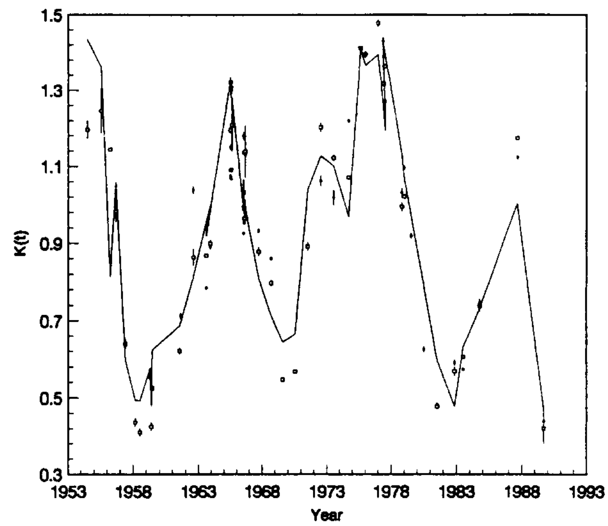

Fig. 7. A plot of K estimated from measurements and from Climax data as a function of time.

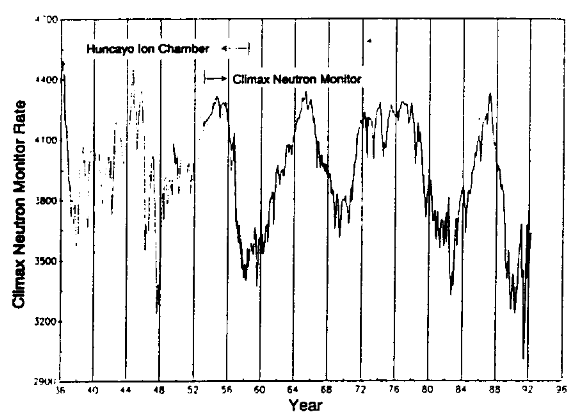

Fig. 8. Long-term cosmic ray intensity variation from carbon-14, ionchamber, and neutron monitor data.

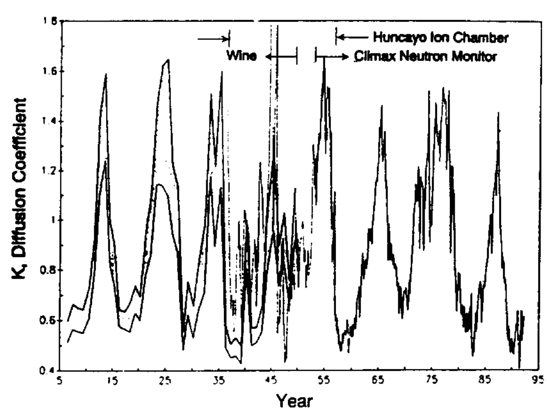

Fig. 9. Longer term cosmic ray intensity variation from carbon-14, ion chamber, and neutron monitor data.

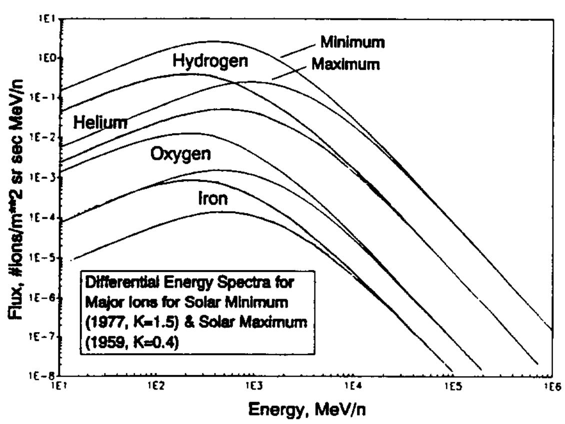

Fig. 10. Derived 1976-77 solar minimum and 1989 solar maximum galactic cosmic ray reference spectra for hydrogen, helium, oxygen, and iron.

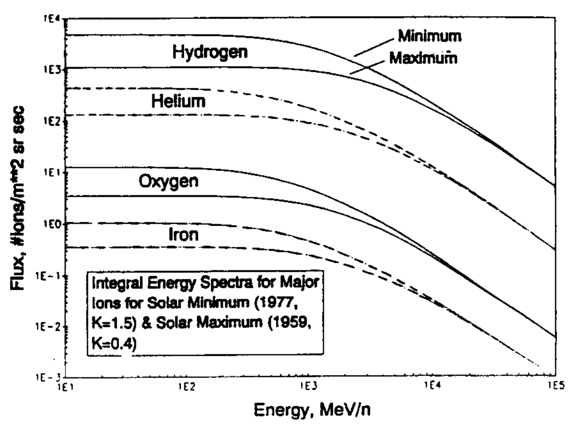

Fig. 11. Integral spectra for 1976-77 solar minimum and 1989 solar maximum for hydrogen, helium, oxygen, and iron.

In order to extend the analysis to time periods before 1936, we used the data on the variation of ^{14}C from Tbilsi (Georgia) wine samples/44/. These data extend from 1909 to 1952 and show the characteristic cosmic ray intensity variations which are related to changing solar activity. This data set overlaps the ion chamber data from Huancayo from 1936 to 1952. Using the measured increase in CO_2 from Mauna Loa, Hawaii from 1957 to 1976/45/ we have subtracted the trend term from the ^{14}C measurements of Burchuladze *et al.*/44/ and normalized it to the ionchamber data. Thus, cosmic ray intensity variations are extended back to 1909. Figure 9 shows the calculated variation of the value of K from solar cycle 15 to solar cycle 22. These results again show that the maximum and minimum values of K(t) chosen above are valid.

REFERENCE COSMIC RAY SPECTRA

The data from 1954 to 1989 indicate that the deepest solar minimum was from the period 1976-77. The deepest maximum occurred in 1989. The ^{14}C measurements from 1909 to 1952 and ionchamber measurements from 1936 to 1955 confirm this observation. Figure 10 shows the differential energy spectra of proton, helium, oxygen, and iron for these solar minima and solar maxima. Thus, our study has defined the *worst-case* galactic cosmic ray intensities. These intensities should be used to study shielding requirements for Mars type missions. Figure 11 shows the integral spectra of hydrogen, helium, oxygen, and iron GCR ions. Using the abundance of other nuclei relative to oxygen as a function of energy per nucleon, one can obtain the differential energy spectra of all ions from hydrogen to nickel.

CONCLUSIONS

We have studied the solar modulation of GCR intensities using the steady-state conventional diffusion-convection theory and assuming the diffusion coefficient can be separated into independent temporal and spatial functions. The differential energy spectra of various nuclei measured between 1954 and 1989 were fit to the model. The deceleration parameter derived from these data correlated well with the Climax neutron monitor rate. However, the form of the correlation differs for odd and even solar cycles. We have also extended the model to longer term modulations using ion chamber and ^{14}C measurements. These records which span nearly 80 years of observations (cycle 15 to 22) suggest that, the 1976-77 was the lowest solar minimum and 1989 was the highest maximum. We have obtained the differential energy spectra of the four constituents which contribute most to the total equivalent dose. We recommend that these spectra along with abundances of other ions relative to oxygen (versus kinetic energy per nucleon), be used in designing spacecraft shielding for interplanetary missions. We wish to emphasize that the focus of this study was not to obtain a detailed description of the heliospheric modulation. Excellent review articles/46,10,47/ are available for that purpose. However, our results obtained a self-consistent model of GCR differential spectra, useful in planning long-term human space missions. This model represents a significant improvement over the the CREME model/7/, and the models of Miroshnichenko and Petrov/48/, and Nymmik *et al.*/49/.

ACKNOWLEDGEMENTS

We are grateful to Dr. Donald Robbins for a critical review of this work. His suggestions have greatly added to the clarity of this paper. We would like to thank Dr. Roger Pyle, University of Chicago, for providing the Climax neutron monitor data. We would like to thank Dr. James Adams Jr. for discussions and Mr. Omar Balatji and Mr. Jonas Chen in digitizing the Tiblisi wine data set.

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