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CONTENTS

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I. INTRODUCTION

We shall study time dependent variations in the production rate of C^{14} resulting from changes in various astrophysical and geophysical factors. The general success of the C^{14} dating method implies that to a first approximation the production rate of C^{14} has been essentially a constant for the last several millenia. However, a variety of phenomena cause changes in the production rate which in turn can produce measurable perturbations in the biospheric C^{14} activity. In particular we shall consider changes in C^{14} production caused by variations in the terrestrial and interplanetary magnetic fields leading to changes in the flux of galactic cosmic rays at the earth; by enhanced fluxes of particles from solar flares; and by variations in the local interstellar cosmic ray flux produced by nearby supernova explosions.

We calculate the yields of C^{14} from the interaction of protons, alpha-particles and high-energy gamma rays as functions of energy. Using models of the modulation of the cosmic ray spectrum by terrestrial and interplanetary magnetic fields and the possible time variations of these fields, we then compute the resultant changes in C^{14} production. Similarly, from measurements of the solar flare particle fluxes, and a diffusion model for possible cosmic ray variations from nearby supernova sources, we calculate the possible C^{14} production variations. Finally, we calculate the resultant changes in the biospheric C^{14} activity using a simple, two-reservoir model for the distribution of exchangeable carbon. From a comparison of these calculations with the observed fluctuations of C^{14} activity, we attempt to deduce the most plausible causes of these fluctuations and at the same time place upper limits on the variations of the terrestrial and interplanetary fields and the intensities of impulsive cosmic ray sources within the last 10^5 years.

II. C^{14} PRODUCTION

In order to study C^{14} variations we must first determine the dependence of the C^{14} production rate on the cosmic-ray energy spectrum. The rate of C^{14} production by cosmic rays incident on the atmosphere may be written:

$$Q = \sum_i \int_0^\infty \pi\varphi_i(E)m_i(E)dE \quad , \qquad (1)$$

where Q is the production rate in C^{14} atoms per second in a cm^2 column of atmosphere; i is the species of cosmic-ray particle (in this calculation only protons, He, C, N, and O nuclei are important); $\varphi_i(E)$ is the differential flux of the i'th particles per $cm^2 \cdot$sec ster Mev per nucleon incident on the atmosphere; and $m_i(E)$ is the total production or yield of C^{14} resulting from the interaction in the atmosphere of a particle of species, i, and initial energy per nucleon, E.

Considering for the sake of brevity only the first and second generation interactions in the build up of the nucleon cascade this yield may be written (Lingenfelter et al. 1965):

$$m_i E) = P_i(E) \int_o^E \sigma_i(E')\exp\left\{\frac{R_i(E')-R_i(E)}{L_i(E',E)}\right\} \frac{dr_i}{dE} dE'$$

$$+ P_i(E) \sum_s \int_o^E dE_s \int_o^E \sigma_{is}(E)f_{is}(E_s,E')\exp\left\{\frac{R_i(E')-R_i(E)}{L_i(E',E)}\right\} \frac{dr_i}{dE} dE'$$

$$\cdot \int_o^{E_s} \sigma_s(E_s)\exp\left\{\frac{R_s(E_s')-R_s(E_s)}{L_s(E_s',E_s)}\right\} \frac{dr_s}{dE_s'} dE_s' + \cdots \qquad . \qquad (2)$$

The first integral term in the equation is the yield of C^{14} produced by the capture of first generation neutrons produced by the incident particle, i. The second term is the yield of C^{14} produced by the capture of second generation neutrons, produced by all first generation nucleons, s, which were produced by the incident particle, i. Similar more lengthy terms describe the production from subsequent generations. $P_i(E)$ is the probability that a neutron, resulting from interactions of the incident particle i of energy E and its secondaries, will be captured to produce

C^{14}. Diffusion calculations by Lingenfelter and Flamm (1964) show that this is a rather slowly varying function of the incident proton energy E varying from 0.35 at 100 Mev and below to 0.65 at a few Bev and above. σ_i and σ_s are the cross sections for neutron production by the incident particle, i, and the secondary nucleons, s, and σ_{is} is the cross section for secondary nucleon production by the incident particle. $f_{is}(E_s,E')$ is the probability that the secondary nucleon produced by the incident particle of energy E' will have an energy between E_s and $E_s + dE_s$. R(E) and dE/dr are the range and differential energy loss of the particles in the atmosphere. $L(E',E)$ is the mean attenuation length of the particles in the energy interval E' to E.

Data on the cross sections for neutron production by protons in air are presented by Lingenfelter et al. (1965). For lack of data on the neutron production in interactions of cosmic-ray He and heavier nuclei with air we have assumed these cross sections to be A^{α} times the cross section for proton-induced production at the same energy per nucleon, where A is the atomic number of the cosmic ray nucleus and α ranges from 2/3 at energies less than 100 Mev/nucleon to 1 at energies greater than 1 Bev/nucleon. We have further assumed that the total cross section for secondary nucleon production is twice that for neutron production. The data on the other parameters have been summarized by Lingenfelter and Flamm (1964) and Lingenfelter et al. (1965)

The resultant C^{14} yields per particle, calculated from equation (2), are shown in Figure 1 as a function of the incident particle rigidity for cosmic-ray protons, He and CNO nuclei incident on the atmosphere. The first generation neutrons account for most of the production for incident proton energies less than 4 Bv. Subsequent generations contribute 0.1 of the total production at 1.5 Bv and 0.5 at 4 Bv. At rigidities greater than 10 Bv the C^{14} yield is assumed to be proportional to the rigidity to the 0.4 power.

Using the measured energy spectra and nuclear abundances of the cosmic ray flux at the top of the atmosphere at solar minimum and solar maximum (Webber, 1967) we can evaluate equation (1) for the polar C^{14} production rate at both times. The calculated solar maximum to minimum C^{14} production ratio of 0.67 is in excellent agreement with the value of 0.70 determined by Lingenfelter (1963) from atmospheric neutron measurements at solar minimum and maximum. Furthermore, using vertical cut-off rigidities as a function of geomagnetic latitude based on a dipole filed ($p_\lambda(Gv) = 14.9 \cos^4\lambda$), we can calculate the latitude dependence of the production

$$Q_\lambda = \sum_i \int_{E_{i\lambda}}^{\infty} \pi\varphi_i(E) m_i(E) dE \quad . \qquad (3)$$

Where $E_{i\lambda}$ is the cut off energy corresponding to p_λ.

Because of the different rigidity dependence of the C^{14} yield for protons and multiply changed nuclei (see Figure 1) the contribution of the latter to the total C^{14} production varies from 32% of the poles to 48% at the equator. The relative latitude variations of the total production thus calculated are in very good agreement with those determined by Lingenfelter (1963). However, because of the compounding of the uncertainties in the cross sections and other parameters, when the interactions of second and higher generations of nucleons become important at energies greater than a few Bev, it is necessary to normalize the absolute C^{14} yields at high energies in order to give agreement with the best estimate of the C^{14} production rate.

The previous determination of the C^{14} production rate by Lingenfelter (1963) was based on normalization of the relative production rate to atmospheric thermal neutron measurements. In particular, the altitude and latitude dependence of the cosmic-ray neutron production was determined from data on the rates of cosmic-ray nuclear-star production and ionization, and on the equilibrium flux of cosmic-ray neutrons in the atmosphere. From this source distribution, arbitrarily normalized to a production rate of 1 neutron per cm^2 column of atmosphere per second at the geomagnetic pole during solar minimum, the energy-dependent, equilibrium neutron flux was computed using the diffusion equation. The relative altitude and latitude dependence of the C^{14} production rate was then calculated from this flux distribution. The absolute normalization of the production rate was determined by normalizing the calculated thermal neutron flux to experimentally determined rates, measured by balloon-born, bare $B^{10}F_3$ counters. Since most of the measurements were not made at solar minimum on maximum, it was arbitrarily assumed that the variation of the relative flux between times of solar maximum and minimum was linearly proportional to the sunspot number. Now, however, it is possible to directly determine the relative flux as a function of time from the equations given above and the measured variation of the cosmic-ray intensity over the last solar cycle.

Lockwood and Webber (1967) have shown that the polar cosmic-ray flux variation between solar minimum and maximum can be written

$$\varphi(P,t) = \varphi(P,t_0)\exp\left\{\eta(t)/P\beta\right\} \quad , \qquad (4)$$

where P and β are the cosmic-ray particle rigidity and relative velocity, respectively; t_0 is the time of solar minimum; and $\eta(t)$ is a function ranging from 0 at t_0 to about -2Bv at solar maximum. The solar modulation function, η, can be directly related to the corrected daily mean Mt. Washington neutron monitor counting rate (Lockwood, personal communication) and Cheltenham ionization chamber rate

(Forbush, 1958); the combined record of these monitors covers a period of three solar cycles back to 1937. Using this temporal dependence of the flux, we have calculated the relative variation of the equilibrium thermal neutron flux which is directly proportioned to the C^{14} production rate defined in equations (2) and (3). From this variation we can then renormalize the relative neutron and C^{14} production rates of Lingenfelter (1963).

For this renormalization we shall use the thermal neutron measurements in the region of the Pfotzer maximum by Yuan (1951) on June 9, July 25, 1948, and January 8, 1949 at 51.8° N. Geomag. Lat.; Soberman (1956) on August 27, 29 1952 at 88.6° N. Geomag. Lat., August 24, 28 1954 at 55° N. Geomag Lat. and September 6, 8, 9, 1953 at 10.1°; Reidy et al. (1962) on August 23, 1960 at 49° N. Geomag. Lat., Smith et al. (1962) on July 20, 1961 at 57° N. Geomag. Lat.; and Miles (1964) on February 6, July 5, 6 and October 22, 23 1962 at 41° N. Geomag. Lat. We have not included the aircraft-born measurements by Hess et al. (1959) which appear to have been affected by local neutron production in the aircraft. The absolute neutron production per second in a cm^2 column of atmosphere at the geomagnetic pole during solar minimum determined from the normalization of each set of measurements is: 7.7 ± 1.6 for Yuan (1951); 9.4 ± 1.4 for Soberman (1956); 8.3 ± 2.1 for Reidy et al. (1962), 9.7 ± 2 for Smith et al. (1962) and 7.2 ± 1.4 for Miles (1964). The weighted mean of these values is 8.35 ± 1.7. This is 7% lower than the value of 9.0 ± 1.8 previously determined by Lingenfelter (1963).

This renormalization gives a global average C^{14} production rate of 2.42 ± 0.48 C^{14}/cm^2 sec during solar minimum (1953-4) and 1.93 ± 0.39 during solar maximum (1957-8). The latitude dependence of the neutron and C^{14} production rates during solar minimum and maximum are tabulated in Table 1. The dependence of the global average C^{14} production rate on the solar modulation function, η , and hence on the daily mean neutron monitor and ionization chamber rates is shown in Figure 2. Using quarterly average values of the Mt. Washington daily mean neutron monitor rate we calculate that the average C^{14} production over the last solar cycle (1955 to 1964) was 2.1 ± 0.4 C^{14}/cm^2 sec. Including the Cheltenham ionization chamber record back to 1937, we find a three cycle average (1937 - 1967) of 2.2 ± 0.4 C^{14}/cm^2 sec.

III. C^{14} ACTIVITY

In order to investigate variations in the C^{14} activity, it is necessary to assume a model for the distribution of exchangeable carbon in the terrestrial reservoir. The relatively long term variations which we discuss quantitatively in the present paper can be investigated by using a two reservoir model: an upper reservoir containing A grams of carbon per cm^2 of the earth's surface, which represents the atmosphere and biosphere and possibly the upper hundred meters of ocean above the thermocline; and a lower reservoir, containing B grams of carbon per cm^2, which represents the oceans (Wood and Libby, 1964; Ramaty, 1965; Houtermans, 1966). The ratio B/A is defined as a parameter ν . If the upper hundred meters of ocean are part of the upper reservoir $\nu \approx 30$, whereas if the entire oceans belong to the lower reservoir $\nu \approx 60$.

Let R_A and R_B be the radiocarbon concentrations in the upper and lower reservoirs, respectively. The differential equations satisfied by the C^{14} contents AR_A and BR_B are (e.g. Ramaty, 1965)

$$\frac{d}{dt}(AR_A) = Q - \frac{AR_A}{\tau} - \frac{AR_A}{T} + \frac{BR_B}{\nu T} \quad , \tag{5}$$

$$\frac{d}{dt}(BR_B) = -\frac{BR_B}{\tau} - \frac{BR_B}{\nu T} + \frac{AR_A}{T} - S \quad , \tag{6}$$

where: Q is the global average C^{14} production which may be time dependent; τ is the mean life of radiocarbon equal to 8300 years; T is the average residence time of a carbon atom in the upper reservoir equal to about 25 years (Wood and Libby, 1964); and S is a possible loss rate from the lower reservoir due to sedimentation.

By assuming that S is time independent and by defining the decay rates in the upper, lower and total reservoirs, respectively, as

$$J_A = \frac{1}{\tau}(A+B)R_A + S(1-T^*/\tau) \quad , \qquad (7)$$

$$J_B = \frac{1}{\tau}(A+B)R_B + S(1+T^*/\nu\tau) \quad , \qquad (8)$$

$$J_t = \frac{1}{\tau}(AR_A + BR_B) + S \quad , \qquad (9)$$

where

$$T^* = \left(\frac{1}{\tau} + \frac{1}{T} + \frac{1}{\nu T}\right)^{-1} \quad ,$$

the solutions of equations (5) and (6) can be written as

$$J_A(t) = \frac{1}{\tau}\int_{-\infty}^{t} e^{(t'-t)/\tau}\, Q(t')dt' + \frac{\nu}{\tau}\int_{-\infty}^{t} e^{(t'-t)/T^*} Q(t')dt' \quad , \qquad (10)$$

$$J_B(t) = \frac{1}{\tau}\int_{-\infty}^{t} e^{(t'-t)/\tau}\, Q(t')dt' - \frac{1}{\tau}\int_{-\infty}^{t} e^{(t'-t)/T^*} Q(t')dt' \quad , \qquad (11)$$

$$J_t(t) = \frac{1}{\tau}\int_{-\infty}^{t} e^{(t'-t)/\tau}\, Q(t')dt' \quad . \qquad (12)$$

In order to evaluate J_A, J_B or J_t at a given time t, it is necessary to perform the integrals in equations (10), (11) and (12), and, therefore, Q(t′) must be known over a time period of at least several mean lives τ prior to t. Since the geophysical and astrophysical factors which determine the C^{14} production are known at best only at the present and possibly over a relatively short time period in the past, arbitrary assumptions would have to be made about the radiocarbon production in the more distant past. However, we can eliminate the need for such arbitrary assumptions by introducting a parameter, R_o, equal to the present ratio between production and decay in the total reservoir,

$$R_o = Q(0)/J_t(0) \quad , \qquad (13)$$

and by transforming the time variable, t, into a new variable, u, which has its origin at the present and increases backward in time. If Q is constant for several mean lives, τ, an equilibrium is established between C^{14} production and decay, and $R_o = 1$. The general success of the C^{14} dating method would imply that even if Q is somewhat variable, R_o must be close to unity.

In terms of the new time variable, u, and the parameter, R_o equations (10) and (11) can be solved for $J_A(u)/J_A(0)$ and $J_B(u)/J_B(0)$:

$$\frac{J_{A,B}(u)}{J_{A,B}(0)} = \exp(\tfrac{u}{\tau}) - \frac{1}{\tau}\int_0^u \exp(\tfrac{u-u'}{\tau}) \frac{Q(u')}{J_{A,B}(0)}\, du' -$$

$$- \frac{1}{\tau}(\nu,-1)\Big[\int_0^{u+U} \exp(\tfrac{u}{\tau} - \tfrac{u'}{T^*}) \frac{Q(u')}{J_{A,B}(0)}\, du'$$

$$- \int_u^{u+U} \exp(\tfrac{u-u'}{T^*}) \frac{Q(u')}{J_{A,B}(0)}\, du'\Big] \quad , \qquad (14)$$

where the ratios $Q(u)/J_{A,B}(0)$ are given by

$$\frac{Q(u)}{J_{A,B}(0)} = \frac{Q(u)}{Q(0)} \frac{R_o}{1 + (\nu,-1)\,\frac{R_o}{\tau}\int_0^U \exp(-\frac{u'}{T^*})\,\frac{Q(u')}{Q(0)}\,du'} \tag{15}$$

and the parameters ν and -1 correspond to A and B, respectively. U tends to infinity, but to make the result exact it is sufficient that it be only much larger than T^*. Thus for a given R_o, equations (14) and (15) can be evaluated at any time u in the past provided that the production function $Q(u')$ is known over the time interval starting at the present and extending somewhat beyond the time considered. The unknown C^{14} production at earlier times is represented by R_o.

The allowed range of values for the parameter, R_o, can be determined from direct C^{14} measurements and the production calculations discussed above. According to Karlen et al. (1966), the specific activity of 19th century wood (which in our model equals R_A/τ) is 13.56 ± 0.07 disintegrations per minute per gram of carbon. The sedimentation rate S was estimated by Libby (1965) to be 0.5 ± 0.3 C^{14} atoms per cm^2 second. Assuming that A+B = 8.3 g/cm^2 (Libby, 1965), from equation (7) we get J_A = 2.38 ± 0.3 disintegrations per cm^2 second. Using the average Q = 2.2 ± 0.4 determined above, we find that the present value of the ratio Q/J_A (normalized to 19th century conditions) equals 0.96 ± 0.29. Solving for R_o, from equation (15) we obtain

$$R_o = \frac{Q(0)/J_{A,B}(0)}{1 - \frac{Q(0)}{J_{A,B}(0)} (\nu,-1) \frac{\nu \bar{T}^*}{\tau}} \quad , \qquad (16)$$

where

$$\bar{T}^* = \int_0^\infty \exp(-\frac{u'}{T^*}) \frac{Q(u')}{Q(0)} du' \quad . \qquad (17)$$

Since $Q(u')/Q(0)$ is not expected to vary very much over several mixing times T^* , we take $\bar{T}^* = T^* = 25$ years. For $\nu=60$, $\tau = 8300$ years, and $Q(0)/J_A(0) = 0.96 \pm 0.29$, we find that $0.75 \le R_o \le 1.61$. This range of values of R_o reflects the uncertainties in the C^{14} production, Q, and removal by sedimentation, S. Since these uncertainties are large, they introduce in turn large uncertainties in the allowed values of R_o . However, as mentioned above, the relative constancy of the C^{14} activity in the past suggests that R_o must be confined to a much narrower range of values. We shall assume, therefore, that R_o is essentially a free parameter to be determined from the study of the long term C^{14} activity variations.

IV. C^{14} VARIATIONS

We shall consider now the various geophysical and astrophysical factors that may influence the global average C^{14} production. Since radiocarbon production and decay appear to be close to equilibrium, we can first treat those factors which may modulate a constant cosmic ray background and then consider separately the variations in such a background arising from discrete cosmic ray sources. The modulations which we shall consider are those associated with variations in the geomagnetic and interplanetary magnetic fields, and the discrete sources which we shall treat are solar flares and supernova explosions.

Geomagnetic and Solar Variations

The effect of a varying geomagnetic field on C^{14} production was considered by a number of authors (Elsasser et al. 1956; Ramaty, 1965 Wada and Inous, 1966; Kogoshi and Hasegawa, 1966; Bucha and Neustupný, 1967). Basically the production at a given geomagnetic latitude λ depends on the magnitude of the vertical cutoff rigidity at that latitude, $P(\lambda) = M/4r^2 \cos^4\lambda$, where r is the earth's radius and M is its dipole moment. Because of the rapid mixing of radiocarbon over the earth's surface and because of the isotropy of the cosmic rays, the only variations of interest are in the magnitude of the geomagnetic dipole and not of its direction.

Variations in the geomagnetic dipole moment over the last 9000 years have been recently summarized by Cox (1969). The reported values of M represent averages of measurements made at different locations under the assumption that the geomagnetic field is a perfect dipole. Since this assumption is known to be only approximately valid, it will introduce some uncertainty in the deduced C^{14} variations. Furthermore, many of the samples used for the geomagnetic measurements were dated by radiocarbon, which, because of the geomagnetic variations themselves, may introduce additional uncertainties in the deduced C^{14} variations, nevertheless, lacking more accurate geomagnetic data, we shall use the data as summarized by Cox (1969) (see Table 2).

In addition to geomagnetic variations, the cosmic ray flux incident on the top of the atmosphere is also influenced by the state of the interplanetary magnetic field. As shown in equation (4) above, this can be characterized by a parameter η , which had the values 0 and -2GV for solar minimum and solar maximum, respectively, of the last solar cycle. From Figure 2 the mean C^{14} production over three solar cycles of 2.2 atoms per cm^2 second corresponds to $\eta = -.7GV$. In the absence of direct measurements outside the solar system, the value of η that characterizes the cosmic ray flux in interstellar space can only be estimated by using indirect arguments. By comparing the measured fluxes of deuterons and helium-3 nuclei in the cosmic rays with those expected from nuclear interactions in interstellar space, Ramaty and Lingenfelter (1969) found that the mean cosmic ray flux in the galaxy can be related to that observed at the earth by a modulating parameter $\eta = 0.35 \pm 0.15$ GV. This value is consistent with the cosmic ray gradient measurements of O'Gallagher and Simpson (1967), who found a $\Delta\eta$ of 0.2 GV between the orbits of the Earth and Mars.

The C^{14} production rates as functions of M, for η equal to -2GV, -.7GV, 0, .35GV and .5GV, are shown in Figure 3. For values of M close to its present value (8×10^{25} gauss cm^3) the production varies approximately like $M^{-0.5}$ which is in agreement with results previously obtained by Elsasser et al. (1956) and Ramaty (1965). However, as is evident in Figure 3, this simple relationship breaks down for much smaller and much larger values of M.

Suess (personal communication) has suggested that, since the cutoff rigidities at all latitudes decrease as M decreases, the global average C^{14} production becomes more sensitive to solar modulation variations. From Figure 3 we see that the change in the global average production rates from solar minimum (OGV) to maximum (-2GV) would have varied from $\Delta Q = 0.48$ C^{14} cm^{-7} sec^{-1} at about 1500 B.P., when the dipole moment had a maximum value of about 11.4×10^{25} gauss cm^3, to $\Delta Q = 0.71$ C^{14} cm^{-2} sec^{-1} at about 5500 B.P., corresponding to a minimum value of 5.1×10^{25} gauss cm^3 . Although the eleven year solar modulation effect on C^{14} activity may be obscured by solar-flare produced increases in C^{14} production, as we shall discuss later, both the solar flares and longer period solar modulation variations would produce changes in C^{14} activity, the magnitude of which would also depend on dipole field variations.

Since there is no information on the long-term variation of η , we shall consider only the C^{14} activity variations that may result from the measured geomagnetic variations. Using the dipole moment variations (Cox 1969), listed in Table 2, and the resultant production variations for the mean value of η (-.7GV), shown in Figure 3, we have evaluated equations (14) and (15) for ν=60, T^* = 25 years, and a range of values of R_o . As mentioned above, for a given value of R_o the C^{14} activity variations can be uniquely determined over almost the entire time period for which the magnetic data is available. The resultant C^{14} variations in the upper reservoir are shown in Figure 4 for R_o = 1 and 1.05 together with the measured radiocarbon variations based on dendrochronological studies (Suess, 1965, 1967).

The minima and maxima at about 1000B.P. and 5500 B.P. correspond, respectively, to the maximal and minimal dipole moments at about 1500 B.P. and 6000 B.P. The magnitude of these extrema depend critically on the value of R_o. As can be seen from Figure 4, the measurements are reasonably well bracketed by $1.0 \leq R_o < 1.05$ and thus the gross features of the C^{14} activity variations can be understood in terms of the variations of the dipole moment.

The limits thus placed on R_o contain information on both the history of cosmic ray intensity and on the rate of radiocarbon sedimentation. For this variation of the dipole moment, a cosmic ray intensity outside the geomagnetic field that is constant in time would give an R_o equal to 1.04. Lower values of R_o imply a higher cosmic ray intensity some time in the past and higher values imply a lower intensity. We shall consider this point in the later discussion of possible C^{14} variations resulting from supernova explosions, and turn now to the implications for the sedimentation rate.

For the upper limit $R_o < 1.05$, we find from equation (16) that

$$Q(0)/J_A(0) = R_o/(1 + \frac{\nu T^*}{\tau} R_o) < 0.88 \qquad ,$$

and since, as determined above, $Q(0) \geq 1.8\ C^{14}\ cm^{-2}\ sec^{-1}$, $J_A(0) \geq 2.04\ C^{14}\ cm^{-2}\ sec^{-1}$. This is consistent with the range $2.38 \pm 0.3\ C^{14}\ cm^{-2}\ sec^{-1}$ given above. However, if C^{14} removal by sedimentation is neglected, $J_A \approx 1.88\ C^{14}\ cm^{-2}\ sec^{-1}$ and this is obviously inconsistent with the lower limit on J_A of $2.04\ C^{14}\ cm^{-2}\ sec^{-1}$ obtained from the upper limit on R_o. These arguments would require, therefore, that radioactive carbon be removed from the exchangeable reservoir at a rate of at least $0.16\ C^{14}\ cm^{-2}\ sec^{-1}$. From the argument presented above, however, it would appear that by decreasing the product νT^* one would increase Q/J_A and therefore decrease the lower limit on J_A. A much lower value of $\nu\bar{T}^*$ however, would be inconsistent with the C^{14} measurements in the deep oceans. In fact, by solving for $J_A(0)$ and $J_B(0)$ in equation (16), we obtain

$$\frac{J_B(0)}{J_A(0)} = \frac{1 - \frac{\bar{T}^*}{\tau} R_o}{1 + \frac{\nu\bar{T}^*}{\tau} R_o} \quad , \qquad (18)$$

which, evaluated for ν=60, $\bar{T}^*$ = 25 years, and R_o = 1.025 ± 0.025, gives J_B/J_A = 0.84 ± 0.005. This is consistent with the measurements of Bien et al. (1962) who found that the radiocarbon activity in the deep oceans is lower than that of the biosphere by about 15% to 23%. If, however, $\nu\bar{T}^*$ were lowered by a factor of about 2 (which would be required for consistency without sedimentation), J_B/J_A would equal 0.92 and this is in disagreement with the C^{14} measurements in the deep oceans.

Solar Flare Variations

The production of C^{14} by the interaction of solar-flare particles with the earth's atmosphere has been studied by Simpson (1960), Lal and Peters (1962) and Lingenfelter and Flamm (1964). The spectrum of solar-flare particles arriving at the earth has been measured by Freier and Webber (1963) who have shown that it can be represented by an exponential in particle rigidity, P.

$$\varphi(P) = \varphi_0 \exp\{-P/P_0\} \quad . \qquad (19)$$

The characteristic rigidity, P_0 , varies with different flares. For the major events of the last solar cycle it has ranged from 50 Mv to 325 Mv. Measurements of the solar particle abundances by Freier (1963) and Biswas et al. (1963) have also shown that the ratios of the differential fluxes per unit rigidity of protons, alpha particle and medium nuclei are essentially independent of rigidity. However, since the solar particles are predominatly of rigidities less than 1 Bv, it can be seen from Figure 1 that C^{14} production by He and CNO is negligible compared to that by protons.

Using the above form of the particle spectra and integrating equation (3) over $d\cos\lambda$, we calculate the global average C^{14} production rate. Moreover, during geomagnetic storms, when the solar flare particles arrive, the vertical cut off rigidities as a function of latitude are different from those of the average undistributed field seen by the cosmic rays. Geomagnetic storms following major solar flares can reduce the effective cutoff rigidities to as small as 20% of the normal cut off rigidities. Thus to place bounds on the solar-flare C^{14} production we have calculated the production rate for both the normal dipole cut off rigidities and for reduced cut off rigidities. These production rates, normalized to an incident solar particle flux of 1p cm^{-2} sec^{-1} of energy greater than 30 Mev, are shown in Figure 5 as a function of the characteristic rigidity, P_0 . As can be seen, the C^{14} production rate is much more strongly dependent on the characteristic rigidity than on the cut off rigidity.

Malitson and Webber (1963) have surveyed the particle intensity measurements for the major solar flares of the last solar cycle and have estimated both the integral flux at the earth and characteristic rigidity for each event. Using these values, listed in Table 3, we have calculated for each flare the global-average C^{14} production, averaged over a year for comparison with the cosmic ray production rate. The total C^{14} production per unit surface area for any event is thus 3×10^7 times the value tabulated. The solar-flare C^{14} production rate averaged over the 11-year solar cycle lies between 0.31 and 0.12 C^{14} cm^{-2} sec^{-1} depending on the reduction of the cut off rigidity. This is between 14% and 6% of the solar-cycle averaged cosmic-ray C^{14} production and as can be seen the bulk of the C^{14} is made in one or two events. Moreover such solar flares produce enough C^{14} to greatly modify the solar-cycle dependence of the total C^{14} production rate (see Figure 6). Therefore, for particularly active solar cycles, such as the last, the 11-year periodicity resulting from solar modulation is completely obscured by solar flare effects. As a result for very active cycles one should not expect to find anti-correction between the atmospheric C^{14} production and sunspot numbers or other indicators of the 11-year solar-cycle activity variation. However, this does not preclude correlations with longer period variations in solar activity, such as those suggested by Stuiver (1961).

The increase in atmospheric C^{14} activity $\Delta J(t)$ resulting from an impulsive incremental increase in C^{14} production ΔQ at a time t=0 may be written

$$\frac{\Delta J_A(t)}{J_A} \approx \frac{\Delta Q}{Q} \frac{\nu}{\tau} \exp\{-t/T^*\} \quad , \qquad (20)$$

where $T^* << \tau$ and J_A and Q are time averaged values. Using the values of these quantities, defined as above, we see that the solar flare of 23 Feb. 1956 may have produced as much as 0.75% increase in the specific activity of atmospheric C^{14} and all flares of the last solar cycle may have produced as much as a 1.1% increase.

Thus measurable solar-flare produced increases in atmospheric C^{14} activity may be associated with periods of great solar activity in the past and such a source may account for some of shorter time variations observed in C^{14} activity in dendrochronologically dated samples. Unfortunately an experimental measurement of solar-flare produced increases during the last solar cycle is not possible because of the much larger increases in atmospheric C^{14} activity produced by nuclear testing during the same period. However, such measurements are possible for known, earlier flares, although the measurements of the energetic particle intensities and spectra are not available for them.

Supernova Variations

Lastly we shall consider possible C^{14} variations caused by supernovae which collectively are the most likely source of most cosmic ray particles. There are two types of increases in C^{14} production which may result from a relatively nearby supernova explosion: a short-term increase produced by a possible gamma ray burst associated with the explosion, and a much longer term increase and subsequent decrease resulting from enhancement of the local background cosmic ray flux by the arrival of cosmic rays accelerated in the explosion.

The possible C^{14} increase produced by a supernova gamma ray pulse has been discussed in detail by Konstantinov and Kocharov (1965, 1967). They point out that gamma rays will interact in the atmosphere and through photonuclear reactions produce neutrons which in turn will be captured by nitrogen to yield C^{14}. Although the photoneutron cross sections for nitrogen and oxygen show a peak at about 25 Mev and decrease at higher energy, the development of a photoelectron-bremsstrahlung cascade causes the neutron and hence C^{14} yield to be essentially constant at about 10^3 C^{14} per erg of gamma rays (> 10 Mev) incident at the top of the atmosphere. This yield in terms of C^{14} atoms per gamma ray photon is comparable to that for cosmic ray protons of the same energy. Estimates of the total energy emitted in gamma rays during a suprnova explosion range from 10^{48} ergs (Colgate, 1968) to 10^{50} ergs (Gould and Burbidge 1965). Konstantinov and Kocharov (1967) have shown that measurable increases in the atmospheric C^{14} activity would have been produced by historical supernovae if their gamma ray emission energies were greater than 10^{49} ergs (see Table 4). Like the C^{14} increases associated with solar flares, these increases would decay with a mean life of T^*. At present no systematic search has been made for such increases, but such a search would prove quite valuable in at least setting an upper limit on the supernova energy emitted in gamma rays.

We now turn to perhaps the most fundamental variation in C^{14} activity, that reflecting local variations in the cosmic ray intensity resulting from nearby supernova sources. In general the cosmic rays may be assumed to come from many supernova randomly distributed throughout the galactic disk. Studies of the production of secondary isotopes, such as D and He^3 (Ramaty and Lingenfelter, 1969) and the light elements (Shapiro and Silverberg, 1968), by cosmic ray interaction in the interstellar medium have shown that the mean amount of matter traversed by local cosmic rays has been between 3 and 4 gm cm^{-2}. In the interstellar gas of the galactic disk, which has a hydrogen density of the order of 1 atom cm^{-3}, this path length corresponds to a mean life of about $2x10^6$ years for relativistic cosmic rays. If we assume that this is the mean life time τ_e

for cosmic ray escape from the galactic disk, then the equilibrium cosmic ray energy density, w, may simply be written

$$w = \frac{f W_{SN} \tau_e}{V} , \qquad (21)$$

where f is the frequency of supernova explosions in the disk; W_{SN} is the total energy of cosmic rays accelerated in a supernova explosion and V is the volume of the disk (4×10^{66} cm^3). The frequency of supernova explosions in the galaxy has been estimated to be about 2×10^{-2} per year (Katgert and Oort, 1967, Kesteven 1968). Therefore the local cosmic ray energy density of 10^{-12} ergs cm^{-3} requires that the total energy of cosmic rays accelerated in a supernova explosion, be of the order of 10^{50} ergs.

Assuming isotropic, three dimensional diffusion, the cosmic ray flux $\varphi(E,t,r)$ arriving from a source of age, t, at a distance, r, may be written:

$$\varphi(E,t,r) = W_{SN} \frac{vN(E)}{4\pi} \left[\frac{4\pi\lambda vt}{3}\right]^{-3/2} \exp\{-r^2/\tfrac{4}{3}\lambda vt\} , \qquad (22)$$

where N(E) is the number distribution of cosmic rays at the source per erg of total cosmic ray energy; v is the cosmic ray particle velocity; and λ is the cosmic ray diffusion mean free path in interstellar space. This expression may be re-written in terms of a dimensionless time, t/t_m , where t_m is the time to maximum for a relativistic particle, equal to $r^2/2\lambda c$. Assuming that $N(E) \sim (mc^2 + E)^{-2.5}$, we get φ (particles per m^2 sec·ster·Mev per nucleon),

$$\varphi = 16 \frac{W_{SN}(10^{50}\ \text{erg})}{r^3(100\ \text{pc})} \beta(1-\beta^2)^{5/4} \left[\frac{t_m}{\beta t} \exp\{-\frac{t_m}{\beta t}\}\right]^{3/2} . \tag{23}$$

Substituting this flux dependence into equations (2) and (3), we then calculate the global average C^{14} production resulting from such a source. This shown in Figure 7, normalized to $W_{SN} = 10^{50}$ ergs and r=100 pc.

The supernova observed in historical times (listed in Table 4) are all so distant that their age is much less than the diffusion time ($t/t_m \ll 1$) and therefore cosmic rays from them have not yet reached the earth. However, the recent discovery of pulsars, which may be neutron-star remnants of supernovae (Gold, 1968 and Pacini, 1968), possibly provides new clues to the age and distance of nearby supernova remnants. Grewing and Priester (1969) have estimated the age of pulsars from the observed periods and the rates of slowing down and the distance can be estimated from the dispersion measure. Surveying the available pulsar data (Maran and Cameron, 1969), we find that for a constant W_{SN} the largest cosmic ray flux at present would be coming for PSR1929+10. This pulsar has a period of 0.227 sec, which from Grewing and Priester's studies would suggest an age of about 10^5 years, and a dispersion measure of 8 electrons $pc \cdot cm^{-3}$, which would give a distance of 80 pc for a free electron density of 0.1 cm^{-3}. These values give a t/t_m of 10 at the present. The maximum flux at the earth from this source would have arrived about 9×10^4 years ago and the flux would now be decreasing with the -3/2 power of the age.

Over the last 8000 years the flux from PSR1929+10 would have decreased by 13%. If we assume that this source is the principal perturbation on more constant background arising for all more distant sources, then the decrease in the total cosmic ray flux during this period would depend on the fraction of the total flux presently contributed by this single source; this in turn depends on the total cosmic energy emitted by the source. As discussed above the values of R_o which are consistent with the dendrochonologically determined C^{14} variations, suggest that the C^{14} production rate 8000 years ago could have been as much as 5% greater. A nearby source such as PSR1929+10 could produce increases of this magnitude. For example $W_{SN} = 3.76 \times 10^{50}$ ergs could produce an increase of 5% and a lesser increase of 1% would result the $W_{SN} = 0.75 \times 10^{50}$ ergs. This can be seen in Fig. 8, which gives the time history of the C^{14} production rate for a local cosmic ray source of the distance and age of PSR1929+10 superimposed upon a constant background. If the cosmic ray flux was as much as 5% higher 8000 years ago and if this excess resulted solely from a 10^5

year old nearby source, then the cosmic rays from this source would make up 38% of the total flux at the present. If the increase were only 1% then the source would only contribute only 8% of the present flux. It is of course much more likely that, if such an increase does exist, it is due to more than one source and from the same diffusion model we see that increases of 5% to 1% would also be expected if all of the present cosmic ray flux came from sources that were 0.25 to 1×10^6 years old.

V. SUMMARY

In summary then we have renormalized the absolute C^{14} production rate based on new atmospheric neutron measurements and from the cosmic ray neutron and ionization monitor records, we have determined the average production rate to be 2.2 ± 0.4 C^{14} $cm^{-2}sec^{-1}$ for the last three solar cycles (1937 to 1967). Because of the uncertainties in the calculation of both the production rate and decay rate of C^{14} we find that the best determination of the ratio of these two rates is obtained from the C^{14} variations determined from dendrochronology. We have shown that the major component of these variations can be understood in terms of measured geomagnetic field variations over the last 10^4 years. Shorter time variations may result from solar modulated cosmic rays, solar flares particles and possibly supernova gamma rays, while longer time variations may reflect changes in the local cosmic ray flux resulting from nearby supernova explosions. All of these variations have been treated quantitatively and further measurements of C^{14} variations can give valuable information on these processes.

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TABLE 1. Cosmic-Ray Neutron and C^{14} Production

(n and C^{14} cm^{-2} sec^{-1})

Solar Minimum, 1953-1954			Solar Maximum, 1957-1958	
Geomagnetic Latitude	Neutron Source	Carbon 14 Production	Neutron Source	Carbon 14 Production
0°	1.37	0.91	1.31	0.86
10°	1.42	0.94	1.35	0.89
20°	1.72	1.13	1.61	1.07
30°	2.56	1.70	2.28	1.51
40°	4.27	2.80	3.46	2.27
50°	6.53	4.20	4.95	3.19
60°	7.92	4.88	5.61	3.50
70°-90°	8.35	4.99	5.61	3.50
Global average	3.81	2.42	2.99	1.93

TABLE 2. Geomagnetic Field Variation

(Cox, 1969)

Years B. P.	Dipole Moment 10^{25} gauss cm^3	Years B. P.	Dipole Moment 10^{25} gauss cm^3
0	8.0	5500	5.1
500	10.5	6000	5.1
1000	11.2	6500	6.4
1500	11.4	7000	8.0
2000	11.3	7500	9.5
2500	10.2	8000	10.2
3000	9.3	8500	11.2
3500	9.0	9000	11.5
4000	8.7	9500	11.8
4500	7.9	10000	12.0
5000	6.4		

TABLE 3. Solar Flare C^{14} Production

Solar Flare		φ_p(>30 Mev) p cm^{-2}	P_0 Mv	Yearly Average Production Rate C^{14} cm^{-2} sec^{-1}	
				Normal Cutoff	20% Normal Cutoff
1956	Feb 23	6.5×10^8	325	0.86	2.33
1957	Jan 20	3×10^8	60	0.006	0.015
1958	Mar 23	2×10^8	55	0.004	0.009
	Jul 7	3×10^8	55	0.005	0.013
1959	May 10	7×10^8	60	0.013	0.034
	Jul 10	8.8×10^8	90	0.039	0.098
	Jul 14	1.1×10^9	70	0.030	0.072
	Jul 16	8.1×10^8	110	0.055	0.14
1960	Nov 12	1.4×10^9	145	0.18	0.45
	Nov 15	5.2×10^8	135	0.056	0.14
1961	Jul 12	1.0×10^8	50	0.002	0.004
	Jul 18	2.1×10^8	135	0.023	0.057

TABLE 4. C^{14} Activity Increases from Supernova Gamma Ray Bursts (Konstantinov and Kocharov, 1967)

Supernova	Date A.D.	Distance (kpc)	% Increase in C^{14} Activity for $W_\gamma = 10^{49}$ ergs.
Crab Nebula	1054	1.1-1.7	0.2-0.4
Tycho Brahe's	1572	0.36-3.3	0.05-4
Kepler's	1604	1-9.9	0.005-0.5
Cassiopeia A	1700	3.4	0.05

FIGURE CAPTIONS

Figure 1. Radiocarbon yield as a function of incident particle rigidity for protons, alpha particles and CNO nuclei.

Figure 2. Global average radiocarbon production as a function of the modulating parameters, η, or of the counting rates of the Mt. Washington neutron monitor and the Cheltenham ion chamber. Solar minimum, 1965, and solar maximum, 1967, correspond to $\eta = 0$ and $\eta = -2GV$, respectively.

Figure 3. Global average radiocarbon production as a function the effective geomagnetic dipole moment for various values of the modulating parameter, η.

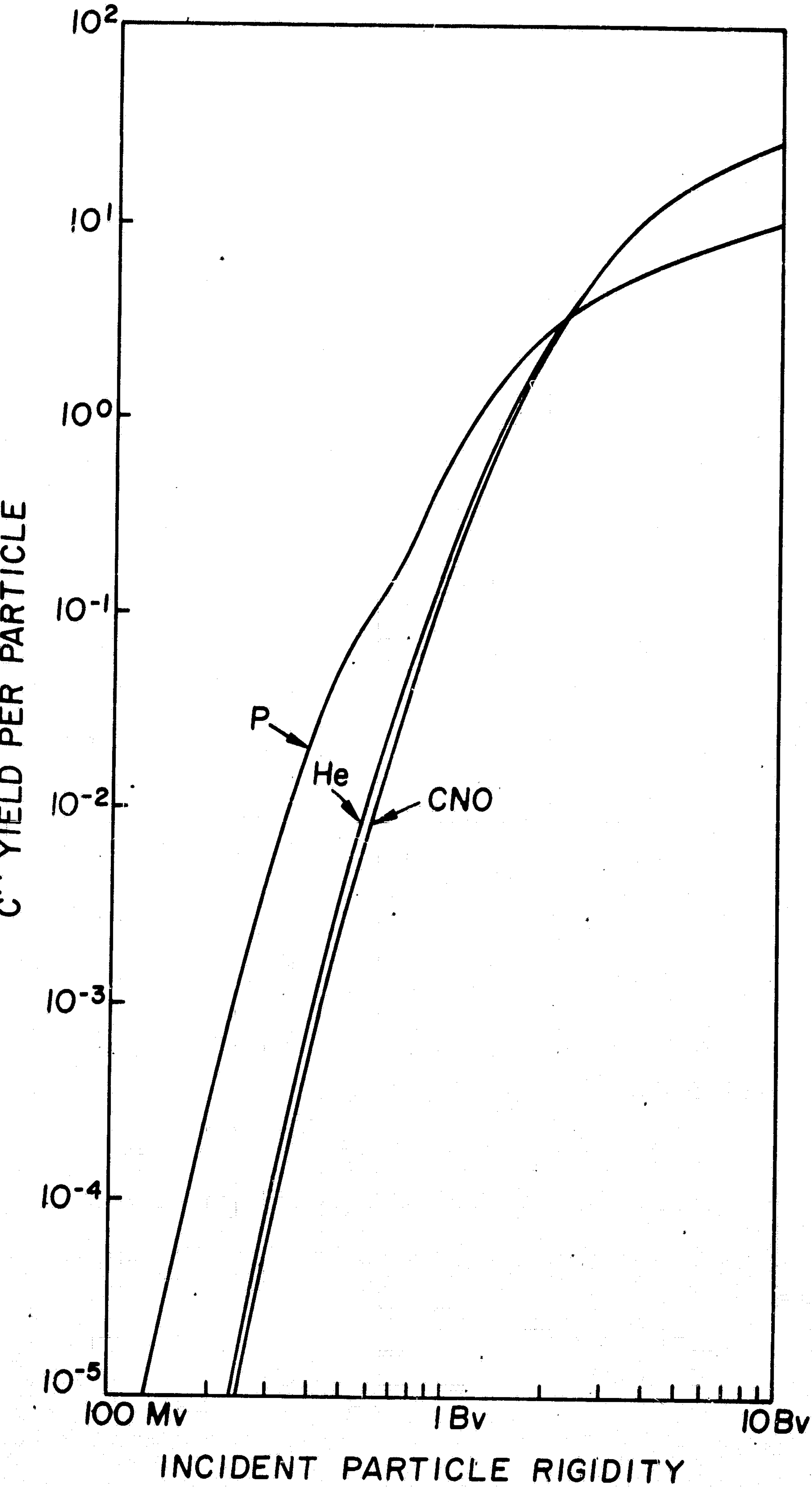
Figure 4. Variation of the radiocarbon excess in the upper reservoir as a function of time for the magnetic data given in Table 2. The measurements are normalized to the activity of 19th century wood. The parameter, R_o, is the ratio between the present production and decay in the total reservoir.

Figure 5. Global average radiocarbon production from solar flare particles as a function of P_o, defined in equation (19), and normalized to 1 proton per cm^2 sec with energy greater than 30 Mev.

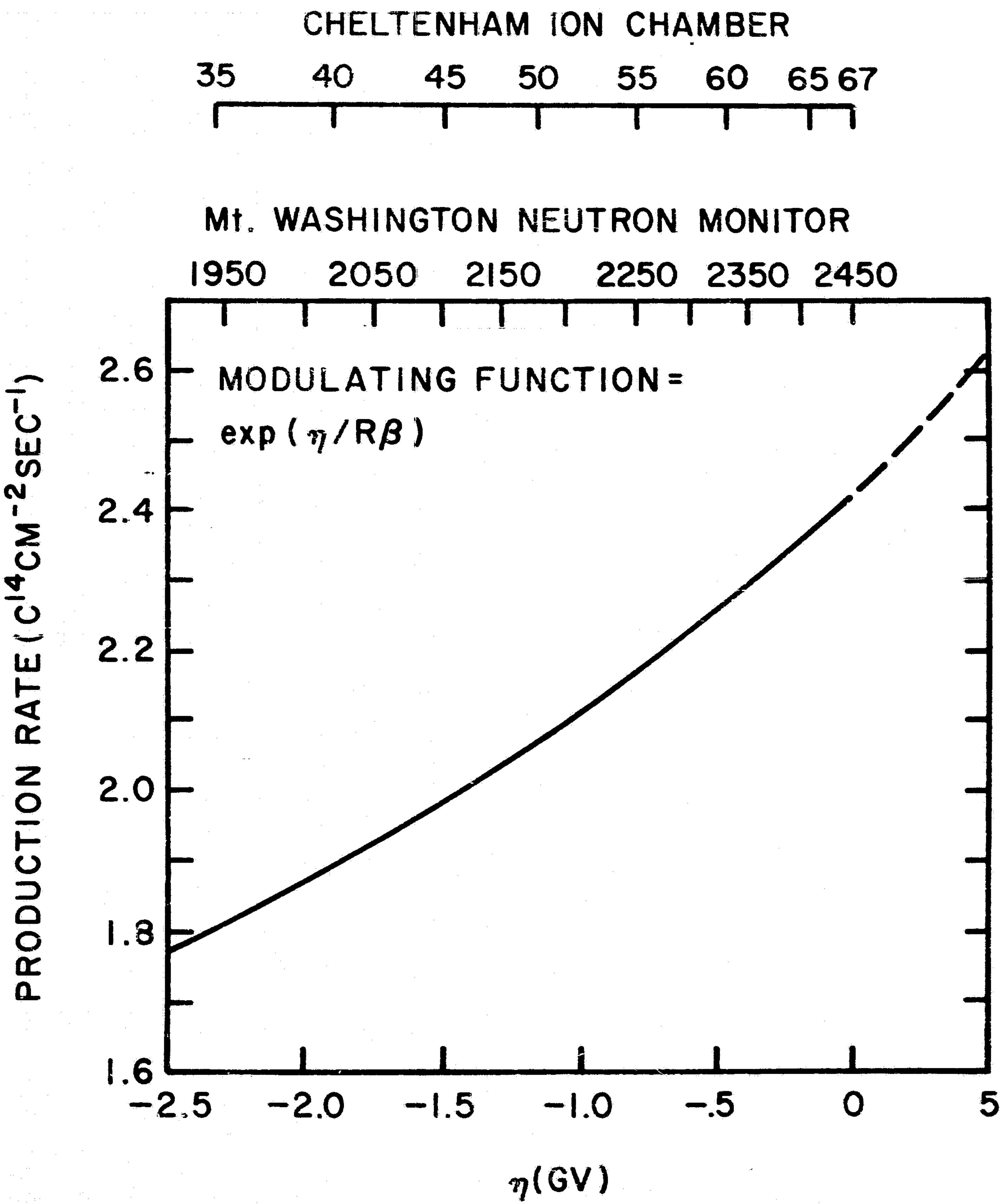
Figure 6. Variation of radiocarbon production over solar cycle 19 due to solar flares and modulation by the interplanetary field. The negative correlation of the radiocarbon production with solar activity, resulting from cosmic-ray modulation is obscured by enhanced particle fluxes from flares.

Figure 7. Global average radiocarbon production from a supernova source as a function time, normalized to the time to maximum at the earth (t_m) of relativistic particles from the supernova.

Figure 8. Global average radiocarbon production as a function of time for cosmic rays from a supernova explosion superimposed on a constant cosmic-ray background flux. For a given distance, age, and diffusion mean free path the energy output of the supernova and the relative contribution of the background are such that during the last 8000 years the radiocarbon production decreased by 5% or 1% for the two curves, respectively.

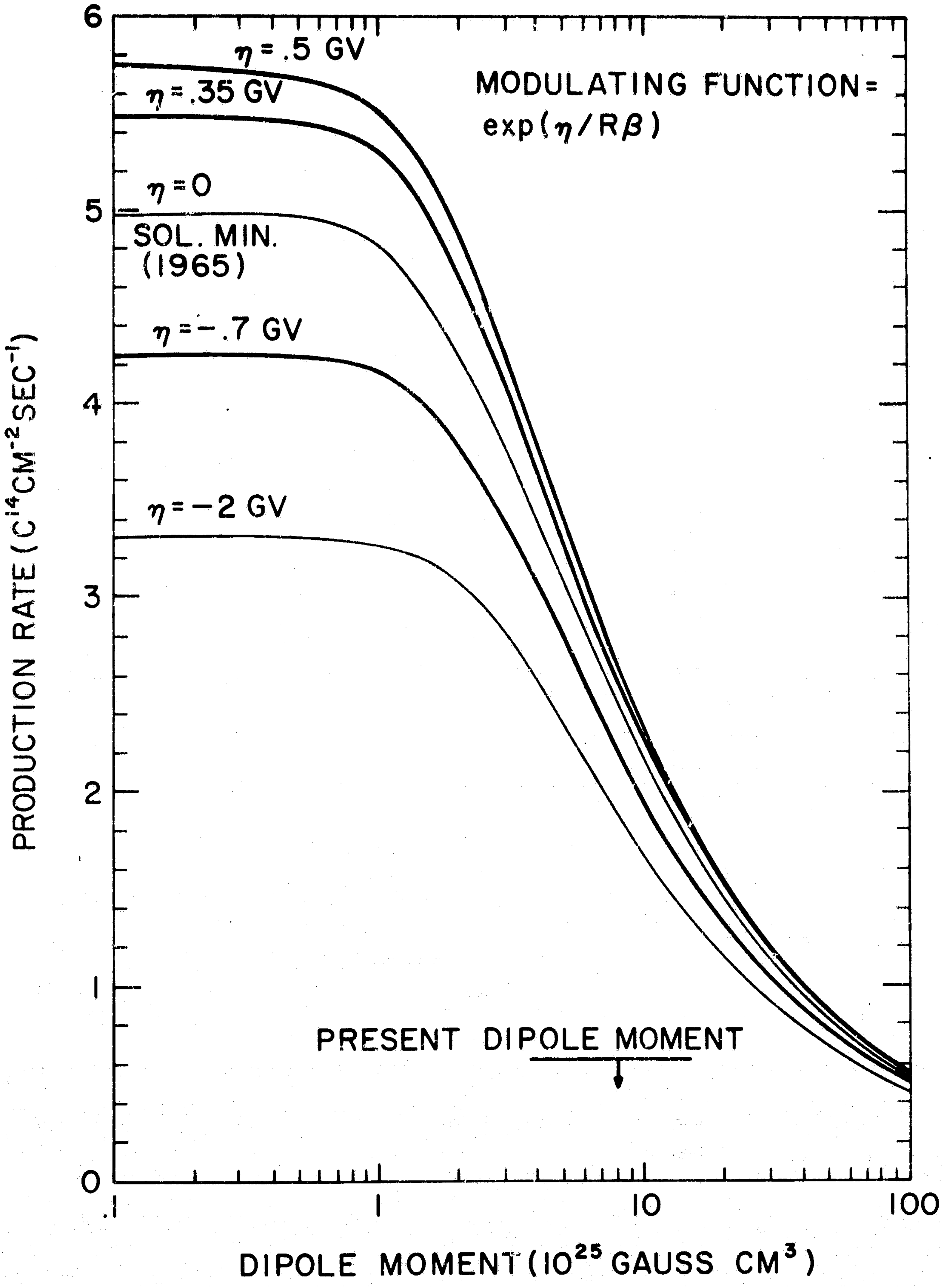


10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
C^{14} YIELD PER PARTICLE
P
He
CNO
100 Mv
1 Bv
10 Bv
INCIDENT PARTICLE RIGIDITY

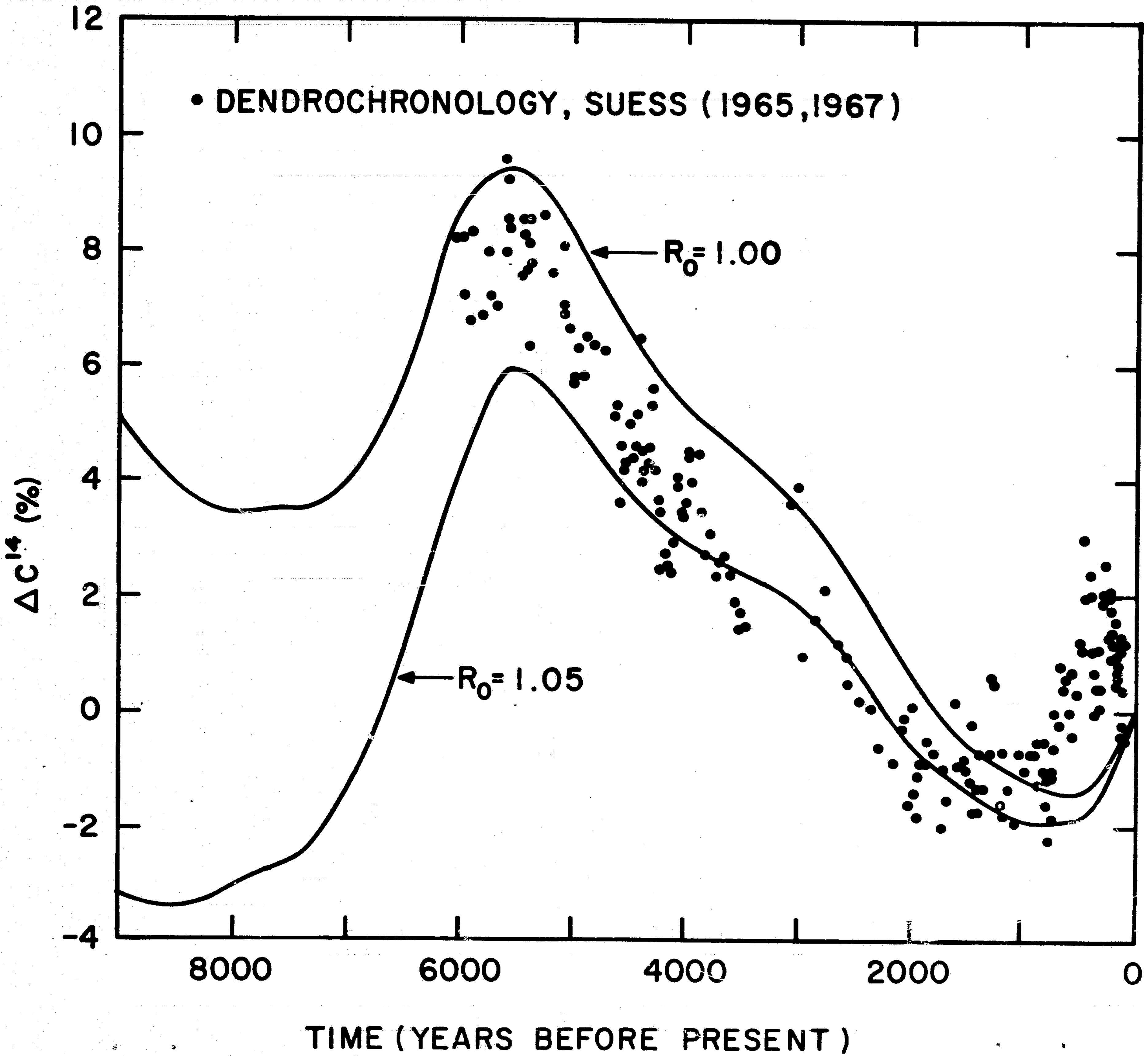


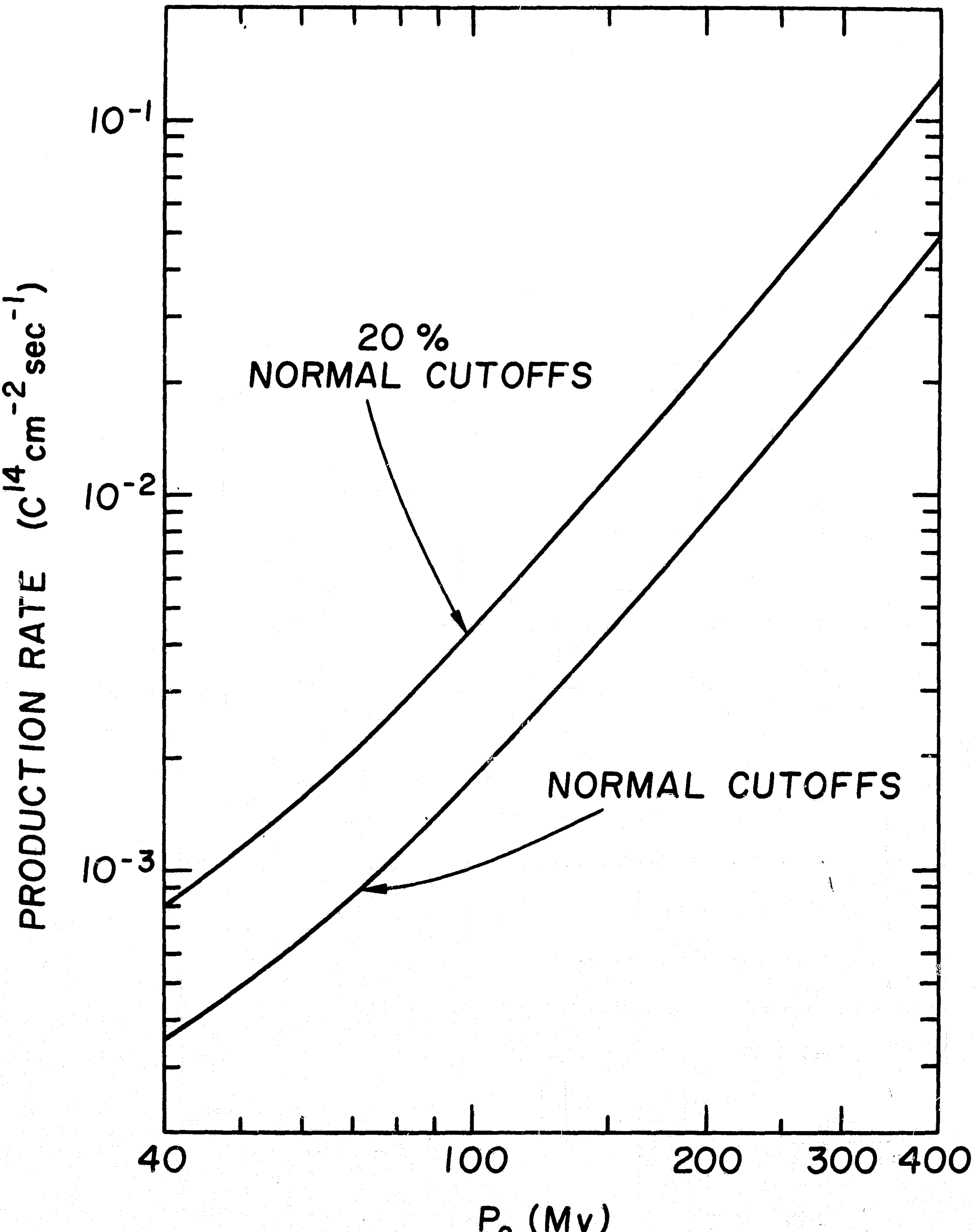
CHELTENHAM ION CHAMBER
35 40 45 50 55 60 65 67
Mt. WASHINGTON NEUTRON MONITOR
1950 2050 2150 2250 2350 2450
MODULATING FUNCTION =
exp (η / Rβ)
PRODUCTION RATE (C14CM-2SEC-1)
2.6 2.4 2.2 2.0 1.8 1.6
-2.5 -2.0 -1.5 -1.0 -.5 0 5
η(GV)

2

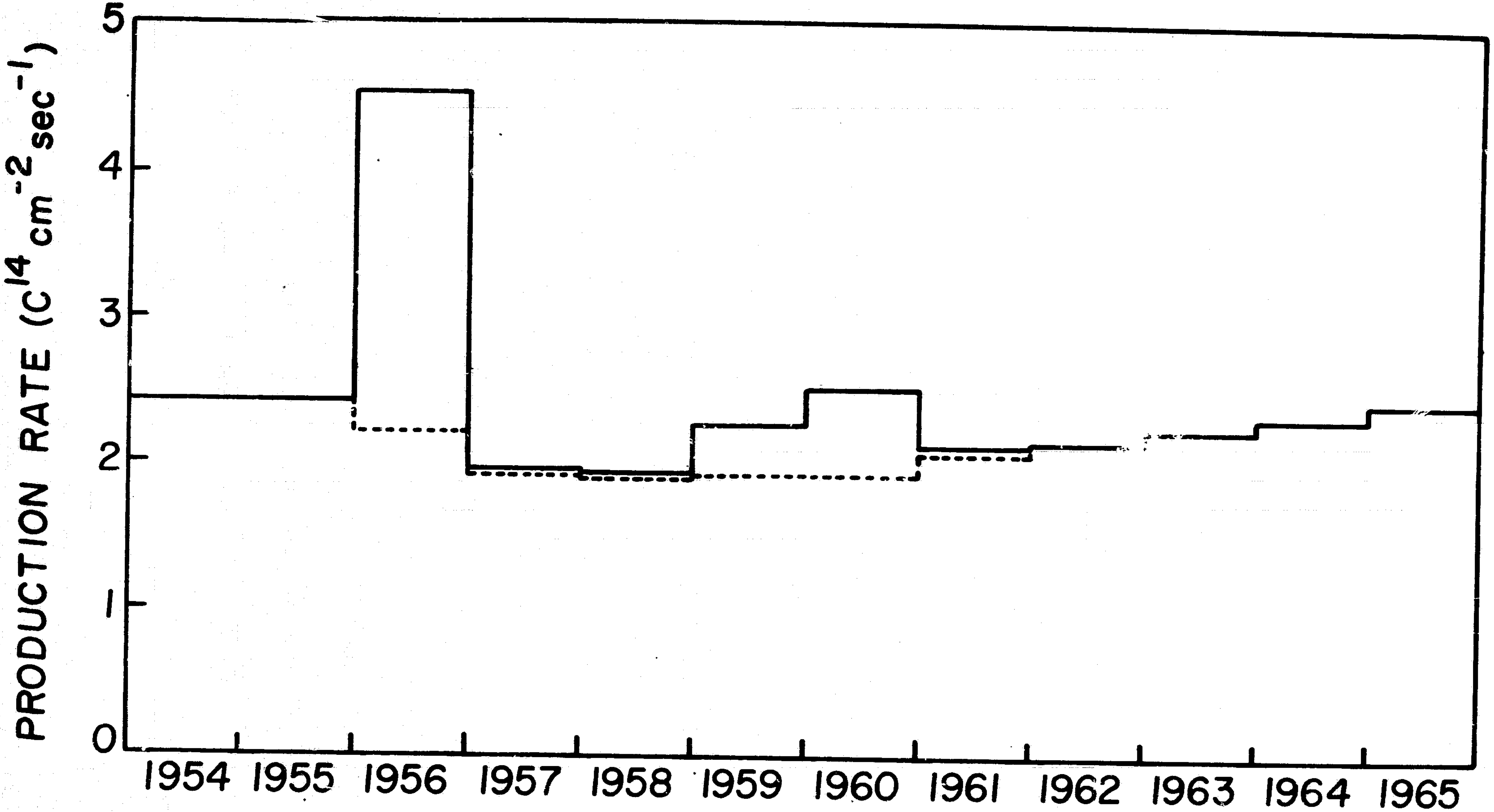


6
5
4
3
2
1
0
.1
1
10
100
η = .5 GV
η = .35 GV
η = 0
SOL. MIN.
(1965)
η = −.7 GV
η = −2 GV
MODULATING FUNCTION =
exp(η/Rβ)
PRESENT DIPOLE MOMENT
PRODUCTION RATE (C14 CM-2 SEC-1)
DIPOLE MOMENT (10^25 GAUSS CM^3)


• DENDROCHRONOLOGY, SUESS (1965,1967)
R_0= 1.00
R_0= 1.05
12
10
8
6
4
2
0
-2
-4
ΔC^{14} (%)
8000
6000
4000
2000
0
TIME (YEARS BEFORE PRESENT)

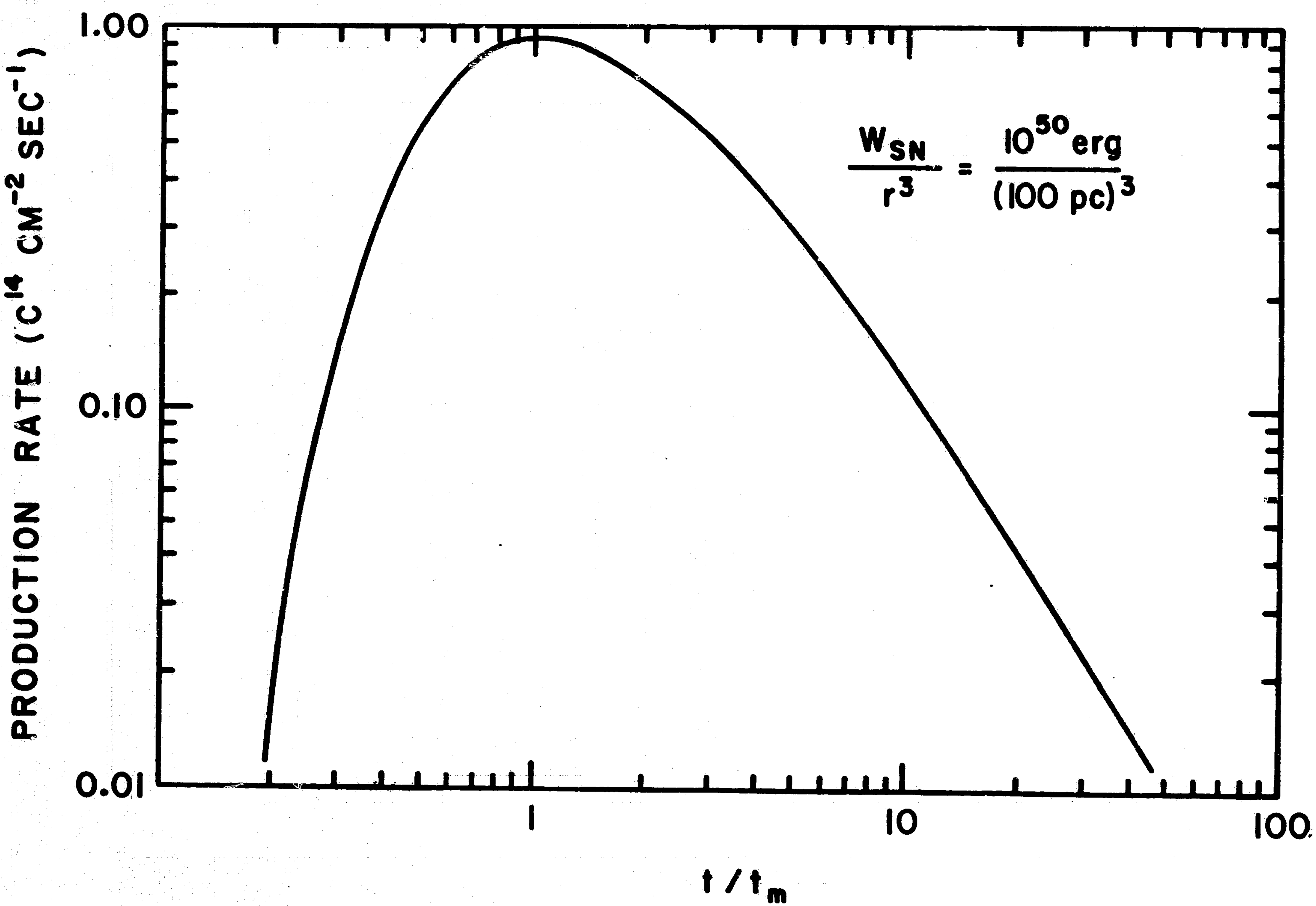


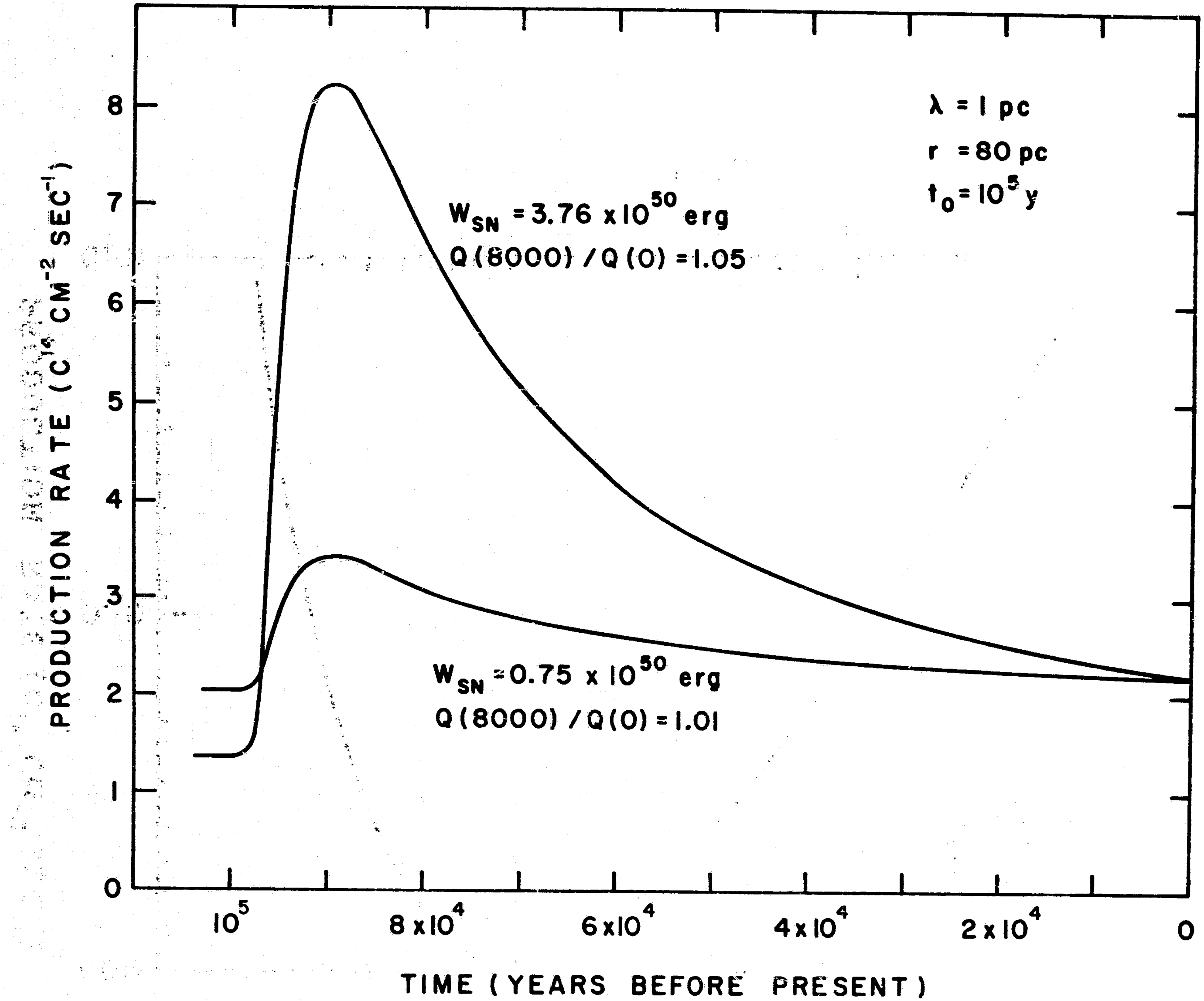
PRODUCTION RATE $(C^{14}cm^{-2}sec^{-1})$
10^{-1}
10^{-2}
10^{-3}
20 %
NORMAL CUTOFFS
NORMAL CUTOFFS
40
100
200
300
400
P_o (Mv)



PRODUCTION RATE (C^{14} cm^{-2} sec^{-1})
5
4
3
2
1
0
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965

6


PRODUCTION RATE (C^{14} CM^{-2} SEC^{-1})
1.00
0.10
0.01
1
10
100
t / t_m
$\frac{W_{SN}}{r^3} = \frac{10^{50}\,\text{erg}}{(100\ \text{pc})^3}$



PRODUCTION RATE (C14 CM-2 SEC-1)
0
1
2
3
4
5
6
7
8
TIME (YEARS BEFORE PRESENT)
10^5
8 x 10^4
6 x 10^4
4 x 10^4
2 x 10^4
0
λ = 1 pc
r = 80 pc
t_0 = 10^5 y
W_SN = 3.76 x 10^50 erg
Q (8000) / Q (0) = 1.05
W_SN = 0.75 x 10^50 erg
Q (8000) / Q (0) = 1.01