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LOW ENERGY COSMIC RAY POSITRONS AND 0.51 MEV GAMMA RAYS FROM THE GALAXY

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Abstract

Large fluxes of low-energy cosmic rays in interstellar space may produce, via unstable CNO beta-emitters, large fluxes of low-energy positrons and a detectable intensity of 0.51 MeV gamma rays. Even though on a galactic scale these cosmic-ray intensities are probably untenable since they conflict with the dynamics of the interstellar medium, they may exist on a smaller scale of the order of the stopping distances of both low-energy cosmic rays and positrons. We compare the results of a detailed calculation with direct positron measurements at the earth and we discuss the observability of the annihilation radiation above the isotropic x-ray background.

Low-Energy Cosmic Ray Positrons and
0.51 MeV Gamma Rays from the Galaxy

I. Introduction

Measurements of the charge composition of cosmic-ray electrons in the energy range of a few MeV to several GeV[1,2,3] have indicated the existence of a detectable flux of cosmic-ray positrons which can best be interpreted as being of galactic origin. At lower energies, a measurement of Cline and Hones[4] has placed an upper limit on the positron flux at about 1 MeV, with a strong possibility that a significant fraction of this flux is of cosmic origin. It has been shown[5] that the measured positron flux above about 100 MeV is consistent with that expected from the decay of positive pions produced in strong interactions between galactic cosmic-rays and the interstellar gas.

Cosmic-ray positrons are produced not only from pion decay, but also from the beta-decay of unstable CNO nuclei produced primarily in relatively low-energy nuclear interactions. Since these interactions are nuclear transmutation, rather than pion-producing interactions, they involve relatively low threshold energies (of the order of 10 MeV rather than 300 MeV). Moreover, the beta-ray positrons are produced with a maximum energy of the order of 1 MeV, whereas the spectrum of pion-decay positrons peaks at about 35 MeV and decreases rapidly toward lower energies. Thus, if there exists a large flux of low-energy galactic cosmic-rays, these particles may provide the most copious source of low-energy cosmic-ray positrons. This source then may contribute significantly to an observable flux near the earth at and below 1 MeV. Furthermore, because of their low energy, it is much more likely for beta-ray positrons to stop and annihilate in the galaxy to produce 0.51 MeV gamma-rays than the positrons from the pion decay process.

Preliminary results on positron production from CNO beta-emitters were reported by Ramaty and Misra[6] and this problem was considered in more detail by Misra[7]. Estimates of positron production from the CNO process were also made by Stecker[8], in connection with galactic 0.51 MeV gamma-radiation, and by Verma[9], in an attempt to account for cosmic-ray electron measurements at low energies[10]. The formal treatment of the problem of galactic positron production in connection with galactic positron annihilation and the resultant gamma-radiation was presented by Stecker[8].

In the present paper we shall summarize the unpublished calculations of Misra[7] and relate them to the problem of 0.51 MeV gamma ray production. Furthermore, we shall discuss the energetics of the problem and relate the results of our calculations to direct positron measurements at the earth and to the question of the observability of the annihilation radiation from the galaxy.

II. Positron Production

The production spectrum of radionuclei, $q_r(E_r)$, per gram of interstellar material per second is given by

$$q_r(E_r) = 4\pi \sum_{i,k} \int dE_i \, j_i(E_i) n_k \sigma_{r,ik}(E_i) f_{r,ik}(E_r;E_i) \quad (1)$$

where E_i and E_r are the kinetic energies per nucleon of the primary and secondary particles respectively, j_i is the intensity of primary cosmic-ray nuclei of type i in interstellar space, n_k is the number density of interstellar gas atoms of type k, $\sigma_{r,ik}$ is the interaction cross section for production of a radionucleus of type r and $f_{r,ik}(E_r;E_i)$ is the normalized energy distribution function for production of a nucleus with energy E_r in an interaction of energy E_i.

Among the variety of beta-emitting nuclei which may be formed in galactic cosmic-ray interactions, only C^{11}, N^{13}, O^{14} and O^{15} contribute significantly to positron production. The principal reactions and their threshold energies are given in Table 1 along with their decay modes and maximum positron energies. The cross sections were summarized by Lingenfelter and Ramaty[11] and by Audouze, Epherre and Reeves[12]. The distribution functions, $f_{r,ik}(E_r;E_i)$ are, in general, unknown. Their detailed form, however, is not important for the present problem since most of the positrons are emitted from nuclei decaying near rest. Thus, the positron production spectrum is determined mainly by the beta-ray spectrum of the parent nuclei. We have assumed that in these p-CNO interactions, the kinetic energy per nucleon is equally distributed among all the secondary nuclei produced, so that

$$f_{r,ik}(E_r;E_i) = \delta\left(E_r - \frac{A_i E_i - Q_{ik}}{A_i + A_k}\right) \quad (2)$$

where A_i and A_k are the mass numbers of the incident and target nuclei respectively.

We have assumed in these calculations that the ratios of H:C:N:O in the interstellar gas are in the proportions $1:3.4 \times 10^{-4}:1.1 \times 10^{-4}:5.8 \times 10^{-4}$, based on the composition of the solar atmosphere[13] and which agree reasonably well with the universal abundances given by Suess and Urey[14] and Cameron[15]

The cosmic-ray energy spectrum and charge composition at solar minimum has been measured by a number of experimenters. The proton spectrum above 20 MeV was summarized by Gloeckler and Jokipii[16] and below this energy is given by Fan et al.[17] The CNO spectra above 50 MeV/nucleon were summarized by Meyer[18]. Because of the lack of data at lower energies, we have assumed that these spectra are of the form $E_i^{0.4}$, normalized to observations at higher energies.

The interstellar primary cosmic-ray intensities can be obtained from the solar minimum spectra by multiplying by a modulation function of the form

$$\mu = \begin{cases} \exp(\eta / R_0 \beta) & \text{for } R < R_0 \\ \exp(\eta / R\beta) & \text{for } R > R_0 \end{cases} \tag{3}$$

where R and β are rigidity and velocity respectively, R_0 is a characteristic transition rigidity that depends on the distribution of interplanetary magnetic field irregularities and η is a parameter which is space and time dependent and defines the total residual modulation. This modulation function was recently discussed by Ramaty and Lingenfelter[19]. They have shown that above a rigidity of 500 MV the observed cosmic-ray H^2 and He^3 spectra are consistent with those obtained from nuclear interactions in interstellar space, with $\eta \approx$ 350 MV and a mean path length for galactic cosmic-rays of $X \approx 4 g/cm^2$. Since there is no information on residual modulation at lower energies, we have to treat R_0 as a free parameter.

Since the lifetimes of the CNO beta emitters are short, the positron production spectrum, q_+, can be obtained directly from the spectra q_r, by taking into account the kinematics of the decay. Thus,

$$q_+(\gamma) = \sum_r \frac{1}{2} \int_1^B \frac{d\gamma^* P(\gamma^*)}{(\gamma^{*2} - 1)^{1/2}} \int_{\gamma_r^-}^{\gamma_r^+} \frac{d\gamma_r \, q_r(\gamma_r)}{(\gamma_r^2 - 1)^{1/2}} \tag{4}$$

where γ_r, γ^*, and γ are the Lorentz factors of the decaying isotope, the positron in the rest frame of the isotope, and the positron in the galactic rest frame, respectively; B is the maximum value of γ^* and is given in Table 1 for the various isotopes involved. The function, $P(\gamma^*)$ is the normalized distribution function for positron production from beta decay processes and is given by Fermi[20] as

$$P(\gamma^*) \propto \gamma^* (\gamma^{*2} - 1)^{1/2} (B - \gamma^*)^2 \tag{5}$$

The limits, $\gamma_r^{\pm}$, are given by

$$\gamma_r^{\pm} = \gamma^* \gamma \pm (\gamma^{*2} - 1)^{1/2} (\gamma^2 - 1)^{1/2} \tag{6}$$

Using the data previously discussed, we have numerically solved equations (1) and (4) for the solar minimum spectrum and for η = 350 MV with various values of R_0. As an extreme assumption, we have also used a power-law cosmic-ray spectrum of the form $E_i^{-2.5}$ with low-energy cutoffs, E_c, at 5, 15 and 100 MeV/nucleon.

The resultant production spectra together with the positrons that would result from pion decay[5] are shown in Figure 1. As can be seen, the CNO source becomes significant only if one assumes large fluxes of low-energy cosmic rays. The large positron production at low energies for R_0 = 200 MV and for the power law spectrum comes primarily from N^{13} and O^{14} produced by low-energy protons via the reactions $O^{16}(p,2p2n)N^{13}$ and $N^{14}(p,n)O^{14}$.

III. The Galactic Positron Spectrum

The positron density in interstellar space $n_+(\gamma)$ can be obtained from the production spectra given in Figure 1 by assuming a steady state and taking into account leakage from the galaxy, positron annihilation, and energy losses by ionization, bremsstrahlung, synchrotron radiation and Compton collisions. We then solve the continuity equation

$$\frac{d}{d\gamma}\left[n_+(\gamma)\,r(\gamma)\right] = \rho\, q_+(\gamma) - \frac{n_+(\gamma)}{\tau_s} \tag{7}$$

where ρ is the density of interstellar material, $r(\gamma)$ is the total energy loss rate and τ_s is the effective positron survival time against leakage and annihilation given by

$$\tau_s = \tau_A \tau_L / (\tau_A + \tau_L) \tag{8}$$

The annihilation lifetime and various energy loss rates used in this calculation were given by Stecker[8]. For the low-energy positrons considered in this paper, ionization losses predominate so that $r(\gamma)$ is proportional to the gas density, ρ.

The leakage lifetime τ_L can be expressed in terms of the mean amount of matter traversed by cosmic-rays, $X = \rho c \beta \tau_L$. As mentioned above, $X \approx 4 g/cm^2$.

The solution of equation (7) for the equilibrium positron flux, $j_+ = n_+ \beta c / 4\pi$ can be written as

$$j_+(\gamma) = \frac{1}{4\pi}\frac{1}{K(\gamma)}\int_{\gamma}^{\infty} d\gamma' q_+(\gamma') \exp\left[-\frac{1}{X}\int_{\gamma}^{\gamma'}\frac{d\gamma''}{K(\gamma'')}\frac{1}{1 + X/X_A(\gamma'')}\right] \quad (9)$$

where $K(\gamma) = r(\gamma)/\rho\beta c$ (in $cm^2 g^{-1}$) is the stopping power of protons in hydrogen, and X_A is an equivalent annihilation-path-length given by[8]

$$X_A(\gamma) = 12.5(\gamma+1)\left[\frac{\gamma^2+4\gamma+1}{\gamma^2-1}\ln\left(\gamma+\sqrt{\gamma^2-1}\right) - \frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]^{-1} g/cm^2 \quad (10)$$

As can be seen, the positron intensity j_+ depends only on the interstellar cosmic ray intensity (through the production function q_+) and on the path length X. Furthermore, at low positron energy, where the range of these particles is much smaller than X, j_+ depends only on the cosmic-ray intensity itself.

The positron fluxes j_+ were obtained by evaluating equation (9) for the production spectra given in Figure 1 and $X = 4g/cm^2$. The results, combined with the calculations of Ramaty and Lingenfelter[5] for positron production via the π-μ-e process, are shown in Figure 2, together with the available positron measurements below 1 GeV.

As can be seen, positrons with energies greater than about 2 MeV come principally from pion decay. At lower energies the relative contribution of the beta-emitters depends critically either on the value of R_o (for η = 350 MV) or on the assumed low-energy cutoff (for a power law spectrum).

The energy densities of cosmic rays for the various spectra discussed above are given in Table 2. As can be seen from Figure 2 and Table 2, unless the energy density in low energy cosmic rays is of the order of a few tens of ev/cm^3, most of the positron flux at $\sim$ 1 MeV would come from pion decay rather than CNO beta-decay and would be small compared to the upper limit of Cline and Hones[4]. If spread uniformly over the galactic disk, such energy densities lead to serious difficulties regarding the stability of the galaxy[21]. On the other hand, since the ranges of both low-energy protons and positrons are short ($\sim$0.1 g/cm^2), the $\sim$ 1 MeV positron measurements sample only a small region of space which may not necessarily be representative of the galaxy as a whole.

For example, consider a 10 MeV proton; its range in hydrogen is 0.05g/cm^2 which, for an ambient density of n atoms per cm^3, leads to a lifetime $t \approx 2 \times 10^5/n$ years. The net streaming distance corresponding to t is $a \approx (4/3\lambda\beta ct)^{1/2}$, where λ is the mean free path for diffusion. If λ = 1 pc, $a \approx 100/n^{1/2}$ pc. Since the rate of supernova explosions in the galaxy (volume $\approx 2 \times 10^{66}$ cm^3) is about

10^{-2} per year, in a spherical volume of radius $100/n^{1/2}$ pc a supernova would be expected to occur once every $2 \times 10^6 n^{3/2}$ years. For $n \gtrsim 1$ atom/cm^3, this time interval is much larger than the lifetime against ionization given above. Therefore, if these protons are produced in supernova explosions and not by more frequent events such as novae or flare stars, their intensities would exhibit sharp maxima close to the time of the explosion and decay to much lower values later on. According to Gold[22] a supernova explosion may liberate as much as 10^{52} ergs. Assuming that 50% of this is in low-energy cosmic-rays, the mean energy density for about $2 \times 10^5/n$ years over a sphere of radius $100/n^{1/2}$ pc would be $\sim 30\ n^{3/2}$ ev/cm^3. This is sufficient to produce a detectable flux of beta-ray positrons. On a galactic scale, however, the same sources of low energy cosmic rays occurring at a frequency of 10^{-2} per year would only produce an average energy density of $3/n$ ev/cm^3. For $n = 1$ this is somewhat large but not inconsistent with the overall energetics of the galaxy.

Since the large fluxes of low-energy cosmic rays are restricted to small volumes and short times, they do not conflict with observations that integrate over large distances, such as the temperature of HI clouds, based on 21cm observations, and the density of free electrons, based on the observed spectrum of non-thermal radio emission. (The connection of these quantities with low-energy cosmic rays was discussed by Balasubrahmanyan et al.[23]). The ~ 1 MeV positron measurements, however, by sampling only a small region of space corresponding to their range of 0.2 g/cm^2, ($t \approx 10^5/n$ years, $a \approx 70/n^{1/2}$ pc) may provide evidence for these locally enhanced fluxes of low-energy cosmic rays.

As can be seen from Figure 2, given a reasonable solar modulation, the positron measurements above a few MeV are all consistent with the calculated spectra from the π-μ-e process. Since the range of protons above pion production threshold is larger than $4 g/cm^2$, these spectra represent mean values over time periods comparable to the positron leakage lifetime from the galaxy. The spatial and temporal inhomogeneities discussed above which would allow large but localized low-energy cosmic ray fluxes, do not apply to this energy domain. The positron spectrum, above a few MeV, obtained from a demodulated cosmic-ray distribution with η = 350 MV, would therefore be a good representation of the interstellar positron intensity.

IV. The 0.51 MeV Gamma-Ray Intensities

The total number of positrons annihilating at or near rest per second per gram of interstellar gas is given by

$$Q_{T,rest} = \int_1^\infty d\gamma' q_+(\gamma') \exp\left[-\frac{1}{X}\int_1^{\gamma'} \frac{d\gamma''}{K(\gamma'')} \frac{1}{1+X/X_A(\gamma'')}\right] \qquad (11)$$

Equation (11) was evaluated numerically for $X = 4 g/cm^2$. The results are shown in Table 3 for the various spectra $q_+(\gamma)$ given in Figure 1. As an extreme case, we have computed the annihilation rates that would result from an interstellar positron flux which is of the same order as the upper limit given by Cline and Hones[4]. Using a total positron intensity of 2 x 10^{-2} particles of ? MeV per cm^2.sec.sr we have computed a maximum annihilation rate corresponding to a positron lifetime against ionization of $10^5/n$ years, and a mean rate corresponding to an average time between supernova explosions of 5 x $10^6 n^{3/2}$ years in a spherical volume of radius $70/n^{1/2}$ pc. These rates are also given in Table 3.

One of us (FWS) has previously shown[8] that the positrons annihilate primarily from an S state of positronium with 75% of these annihilations producing a three-photon continuum rather than a two-photon line at 0.51 MeV. Therefore, on the average, one 0.51 MeV photon is produced for every two positrons which annihilate. Thus, the intensity of 0.51 MeV gamma rays observed along the line of sight as a function of galactic coordinates is given by

$$I_{0.51}(l^{II}, b^{II}) = Q_{T,rest}\, M(l^{II}, b^{II})/8\pi \qquad (12)$$

where $M(l^{II},b^{II})$ in g/cm^2 is the amount of interstellar gas in the direction of observation. The resultant gamma-ray intensities for various directions of observation are given in Table 4. The values of $M(l^{II},b^{II})$ obtained from 21 cm observations are taken from Ginzburg and Syrovatskii[24]. The values of $M(l^{II},b^{II})$ designated by "missing mass hypothesis" are based on the discussion of Stecker[25] as needed to explain the recent observations of 100 MeV gamma-rays from the galaxy[26] as due to bremsstrahlung and π°-production.

As discussed in the previous paper[8], $I_{0.51}(l^{II},b^{II})$ must be greater than 3 x $10^{-4} cm^{-2} sr^{-1} sec^{-1}$ in order to be observable above the X-ray background continuum by a detector with an energy resolution of 5 keV which is the theoretical width of the 0.51 MeV line. This intensity is therefore an absolute lower limit on the 0.51 MeV line intensity which must be present in order for the annihilation line to ever be detected. By comparing this lower limit with the calculated intensities given in Table 4, we see that the annihilation radiation could only be detected toward the galactic center, and, with the "missing mass hypothesis", probably also as a disc average. The calculated gamma-ray fluxes, however, were obtained by assuming that the primary cosmic-ray intensities are spread uniformly along the line of sight over which the annihilation is formed. Such an assumption, for the demodulated cosmic ray spectrum with η = 350 MV and R_o = 200 MV and for the power law distribution, requires a mean cosmic-ray energy density of $\sim$ 50 ev/cm^3 in order to produce a detectable annihilation line. This energy density is at least an order of magnitude higher than that allowed by the general dynamics of the interstellar medium[21]. The energy requirements for the power-law spectrum with E_c = 100 MeV/nuc are smaller and therefore not necessarily inconsistent with the energy arguments mentioned above. A primary cosmic-ray spectrum of this form, however, conflicts with the H^2 and He^3 calculations[19] and possibly with the positron measurements in the 10 to 10^3 MeV region (see Figure 2), and therefore is probably not a good representation of the overall galactic cosmic-ray distribution.

We conclude that the 0.51 MeV annihilation gamma-ray intensity, produced by positrons from both pion and CNO beta emitters for a homogeneous disc model will be smaller than the observed X-ray background[27] and hence be unobservable.

As can be seen from Table 4, however, if the positron measurement at 1 MeV of Cline and Hones[4] is regarded as real flux rather than an upper limit and is spread uniformly along the line of sight, the annihilation line would be observable, both toward the galactic center and as a disc average. However, if these 1 MeV positrons are produced in supernova explosions and exhibit spatial and temporal inhomogeneities corresponding to their short ranges, the resultant gamma-ray flux would again be below the x-ray background and unobservable.

Since the galactic center is known to be an intense source of high-energy gamma-rays[26] and since the energy arguments that we have used do not necessarily hold for that region, the galactic center may be a detectable source of 0.51 MeV gamma rays. It may thus be more profitable to look for this radiation with a high-spatial-resolution detector than to look for a diffuse galactic flux. This argument is valid even if a diffuse flux is detectable, since as can be seen from Table 4, such a flux would still be more intense toward the galactic center.

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Figure Captions

1. Positron production spectra per gram of interstellar material using a power law cosmic ray spectrum with various low-energy cutoffs, E_c, and demodulated solar minimum spectra with various values of η and R_o.

2. Positron intensities in interstellar space together with the available positron measurements below 1 Bev.

Table 1

Beta Emitter and Decay Mode	Maximum Positron Energy (Mev)	Production Mode	Threshold Energy (Mev)
$C^{11} \rightarrow$ $B^{11} + \beta^+ + \nu$	0.97	$C^{12}(p,pn)\,C^{11}$ $N^{14}(p,2p2n)C^{11}$ $O^{16}(p,3p3n)C^{11}$	20.2 13.1 28.6
$N^{13} \rightarrow$ $C^{13} + \beta^+ + \nu$	1.19	$N^{14}(p,pn)N^{13}$ $O^{16}(p,2p2n)N^{13}$	11.3 5.54
$O^{14} \rightarrow$ $N^{14} + \beta^+ + \nu$	1.86	$N^{14}(p,n)O^{14}$	6.4
$O^{15} \rightarrow$ $N^{15} + \beta^+ + \nu$	1.73	$O^{16}(p,pn)O^{15}$	16.54

Table 2

Cosmic Ray Energy Density (ev/cm^3)

Solar Minimum	η = 350MV (E ≥ 5 $\frac{Mev}{Nucl}$)		Power Law		
	R_o = 500MV	R_o = 200MV	E_c = 100 $\frac{Mev}{nucl}$	E_c = 15 $\frac{Mev}{nucl}$	E_c = 5 $\frac{Mev}{nucl}$
0.5	0.6	57	3.1	17	50

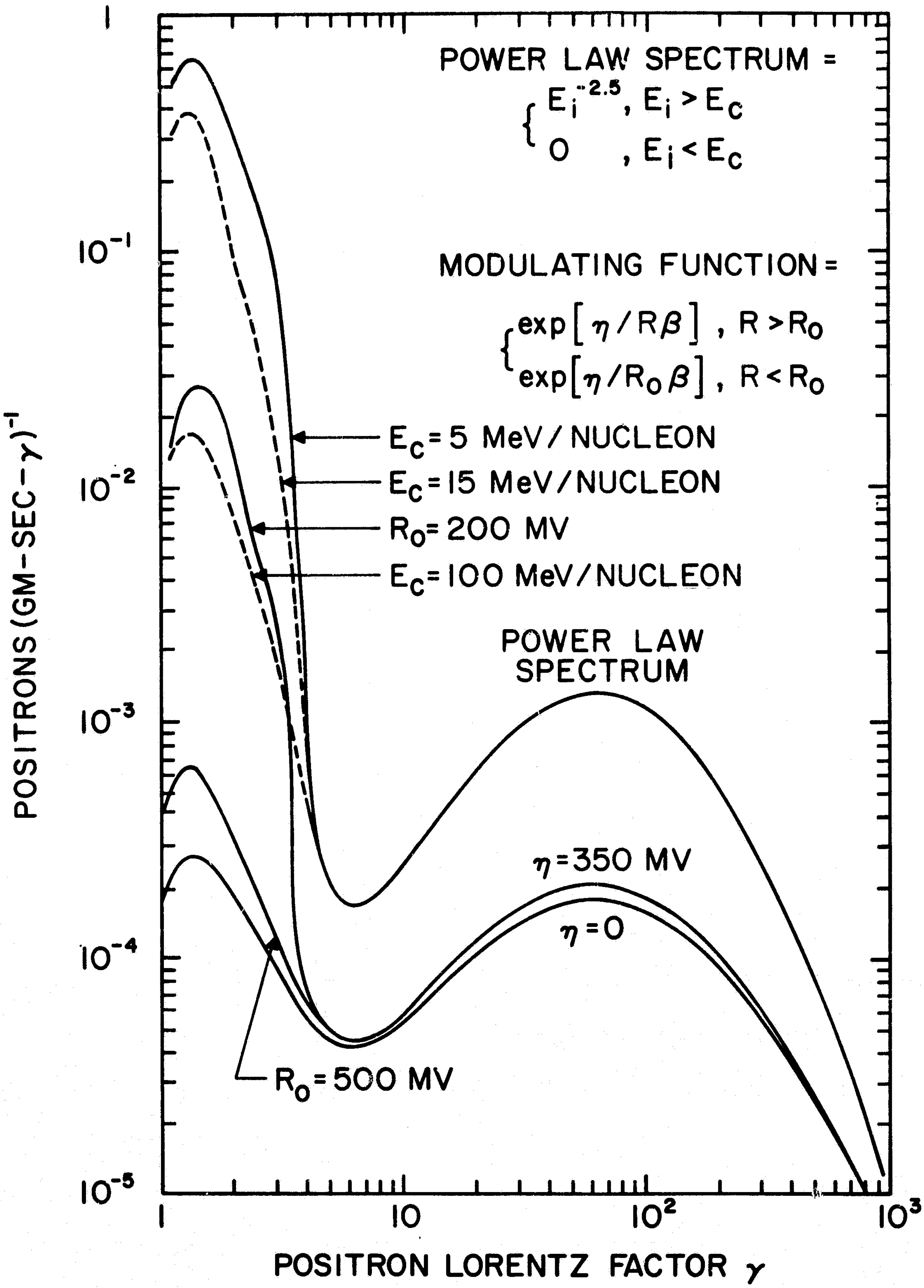
Table 3

Positron Annihilation Rates ($g^{-1}\ sec^{-1}$)

Solar Minimum	η = 350MV		Power Law		$j_+ = 2x10^{-2} cm^{-2} sec^{-1} sr^{-1}$	
	R_o = 500MV	R_o = 200MV	$E_c = 100 \frac{Mev}{Nucl}$	$E_c = 5 \frac{Mev}{Nucl}$	Mean	Maximum
$1.1x10^{-3}$	$1.8x10^{-3}$	$4.3x10^{-2}$	$3.3x10^{-2}$	$1.3x10^{-1}$	$\frac{2.2x10^{-2}}{n^{5/2}}$	0.5

Table 4

	Solar Minimum	η = 350MV R_o = 500MV	R_o = 200MV	Power Law $E_c = 100 \frac{Mev}{Nucl}$	$E_c = 5 \frac{Mev}{Nucl}$	$j_+ = 2x10^{-2} cm^{-2} sec^{-1} sr^{-1}$ Mean	Maximum
Average (including Halo) (21 cm) $\frac{1}{4\pi}\int dl^{II} \sin b^{II} db^{II} M(l^{II}, b^{II}) \simeq 1.6 \times 10^{-3}$	$7.0x10^{-8}$	$1.1x10^{-7}$	$2.8x10^{-6}$	$2.1x10^{-6}$	$8.3x10^{-6}$	$\frac{1.4x10^{-6}}{n^{5/2}}$	$3.2x10^{-5}$
Anticenter (21 cm) $M(\pi,0) \simeq 1.2x10^{-2}$	$5.6x10^{-7}$	$8.6x10^{-7}$	$2.1x10^{-5}$	$1.6x10^{-5}$	$6.2x10^{-5}$	$\frac{1.0x10^{-5}}{n^{5/2}}$	$2.4x10^{-4}$
Galactic Center (21 cm) $M(0,0) \simeq 6x10^{-2}$	$2.7x10^{-6}$	$4.3x10^{-6}$	$1.0x10^{-4}$	$7.9x10^{-6}$	$3.1x10^{-4}$	$\frac{5.3x10^{-5}}{n^{5/2}}$	$1.2x10^{-3}$
Disc Average (missing mass hypothesis) $\frac{1}{2\pi}\int dl^{II} M(l^{II}, 0) \simeq 6 \times 10^{-2}$	$2.7x10^{-6}$	$4.3x10^{-6}$	$1.0x10^{-4}$	$7.9x10^{-5}$	$3.1x10^{-4}$	$\frac{5.3x10^{-5}}{n^{5/2}}$	$1.2x10^{-3}$
Galactic Center (missing mass hypothesis) $M(0,0) \simeq 0.2$	$8.8x10^{-6}$	$1.4x10^{-5}$	$3.4x10^{-4}$	$2.6x10^{-4}$	$1.0x10^{-3}$	$\frac{1.7x10^{-4}}{n^{5/2}}$	$4.0x10^{-3}$



POWER LAW SPECTRUM =
{ $E_i^{-2.5}$, $E_i > E_c$
0 , $E_i < E_c$
MODULATING FUNCTION =
{ exp[η/Rβ] , R > R_0
exp[η/R_0β] , R < R_0
E_c = 5 MeV/NUCLEON
E_c = 15 MeV/NUCLEON
R_0 = 200 MV
E_c = 100 MeV/NUCLEON
POWER LAW SPECTRUM
η = 350 MV
η = 0
R_0 = 500 MV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
POSITRONS (GM-SEC-γ)$^{-1}$
1
10
10^2
10^3
POSITRON LORENTZ FACTOR γ

Fig. 1

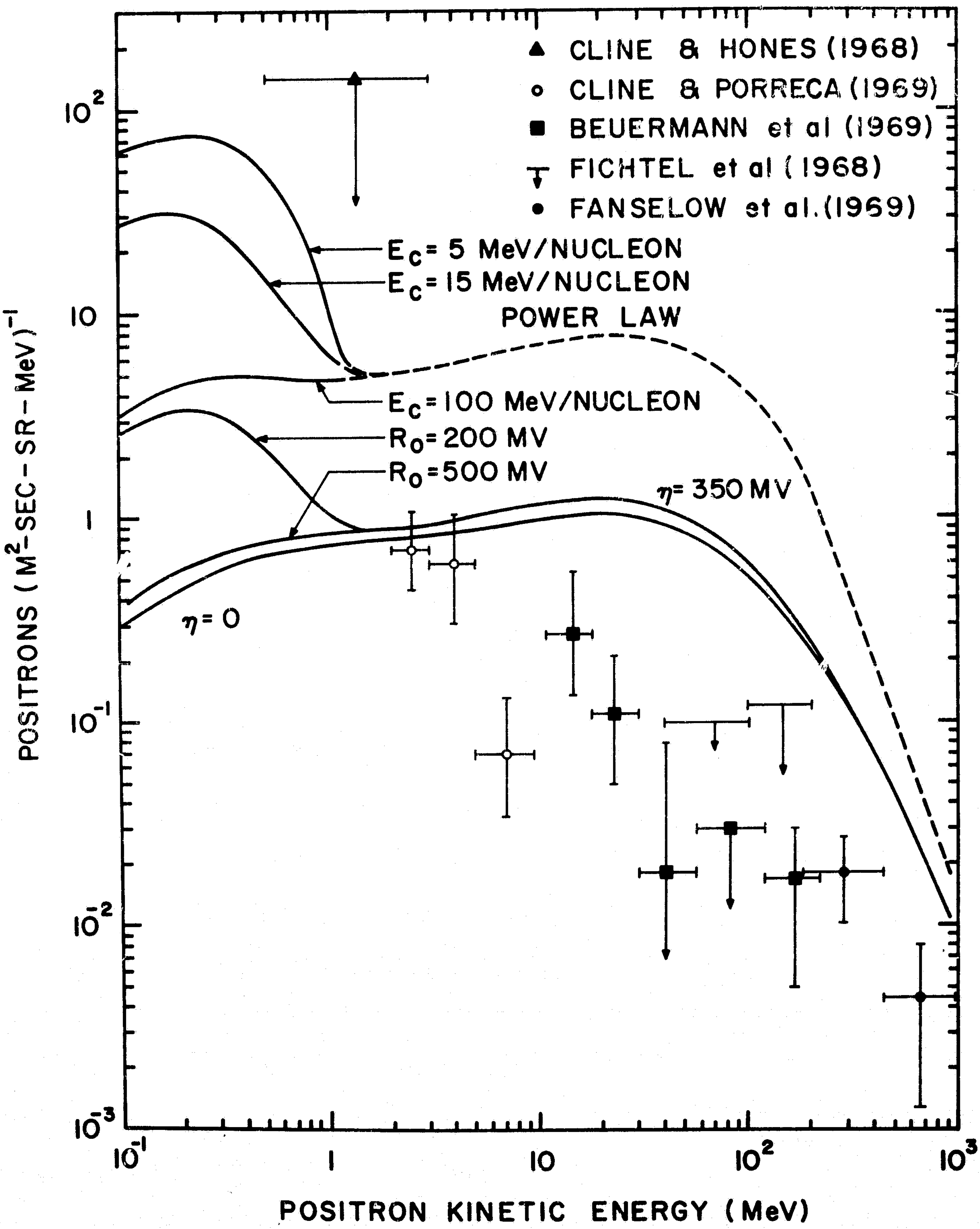

CLINE & HONES (1968)
CLINE & PORRECA (1969)
BEUERMANN et al (1969)
FICHTEL et al (1968)
FANSELOW et al.(1969)
E_C = 5 MeV/NUCLEON
E_C = 15 MeV/NUCLEON
POWER LAW
E_C = 100 MeV/NUCLEON
R_O = 200 MV
R_O = 500 MV
η = 350 MV
η = 0
POSITRONS $(M^2$-SEC-SR-MeV$)^{-1}$
POSITRON KINETIC ENERGY (MeV)

Fig. 2