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Technical Memorandum 82155

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(NASA-TM-82155) COSMIC RAY ANTIPROTONS IN
CLOSED GALAXY MODEL (NASA) 24 p
HC A02/MF A01

N81-29061

CSCL 03B

Unclas
G3/93 31116

JUNE 1981



National Aeronautics and
Space Administration

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COSMIC RAY ANTIPROTONS IN THE CLOSED GALAXY MODEL

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Received 1981 March 24

Abstract

We have made a calculation of the flux of secondary antiprotons expected for the leaky-box model and for the closed galaxy model of Peters and Westergaard (1977). The \bar{p}/p ratio observed at several GeV is a factor of 4 higher than the prediction for the leaky-box model but is consistent with that predicted for the closed galaxy model. New low energy data is not consistent with either model. The possibility of a primary antiproton component is discussed.

Subject headings: cosmic rays: abundances-cosmic rays: general-galaxies:
Milky Way-galaxies: Structure-particle acceleration.

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1. Introduction

Irrespective of whether or not there are primary antiprotons in the cosmic rays, a secondary component resulting from the nuclear interaction of cosmic rays in the interstellar medium will exist. The magnitude of this secondary component depends critically on how cosmic rays are stored in and propagate through the galaxy.

The first reliable predictions of the antiproton to proton ratio (\bar{p}/p) were made by Gaisser and Maurer (1973) shortly after results on \bar{p} production rates in pp collisions became available from the CERN intersecting storage rings (for references, see Gaisser and Maurer, 1973). Their prediction was for the 'homogeneous' or 'leaky-box' model of cosmic ray propagation in which the rates of production and probabilities of escape of cosmic rays from the galaxy are uniform throughout the containment volume. In this model, the \bar{p}/p ratio depends only on the shape of the proton spectrum and on the mean escape length, x_e . The prediction of Gaisser and Maurer (1973) for an $E^{-2.6}$ proton spectrum (E is total energy) and a mean escape length of 5 g/cm^2 (the interstellar medium was taken to be composed entirely of hydrogen) is shown in Figure 1. Later predictions by Badhwar et al. (1975) appear to be in error as pointed out by Szabelski, Wdowczyk and Wolfendale (1980) and Tan and Ng (1981).

Steigman (1977) emphasized the astrophysical and cosmological significance of cosmic ray antiprotons and made estimates of the \bar{p}/p ratio expected for the closed galaxy models of Rasmussen and Peters (1975) and Peters and Westergaard (1977) using the (incorrect?) Badhwar et al. (1975) predictions. The predicted \bar{p}/p ratio varied by up to a factor of 10 between the leaky-box and closed galaxy models.

The first cosmic ray antiproton observations were made by Golden et al. (1979) and by Bogomolov et al. (1979) and were found to give a \bar{p}/p ratio

significantly higher than that predicted for the leaky-box model. The recent low energy result of Buffington, Schindler and Pennypacker (1981) confirms this trend. These data are shown in Figure 1. Szabelski et al. (1980) have used the observed high energy \bar{p}/p ratio in conjunction with their calculations to estimate the mean escape length of antiprotons for the leaky-box model. They found this to be a factor of 5 to 10 higher than that inferred from the ratio of light to medium cosmic ray nuclei (eg. boron/carbon). From this inconsistency, they suggested that the distribution of pathlengths may not be exponential (leaky-box model), but might have a longer 'tail'.

Gaisser, Owens and Steigman (1981) suggested that a re-examination of the closed galaxy model of Peters and Westergaard (1977) was merited by the observations. A similar conclusion was also reached by Stephens (1981a) who found that the observed \bar{p}/p ratio was about halfway between that predicted for the leaky-box model and that predicted for the Rasmussen and Peters (1975) closed galaxy model (Stephens, 1981b). Stephens (1981a) also considered the leaky box model and the nested leaky box model of Cowsik and Wilson (1973). The ratio predicted for the latter model was lower than for the leaky box model and gave a worse fit to the data. In the present paper, we consider cosmic ray antiprotons in the context of the closed galaxy model of Peters and Westergaard (1977). Cosmic ray positrons in this model are discussed in a separate paper (Protheroe, 1981).

2. The Model

In the version of closed galaxy model proposed by Peters and Westergaard (1977), hereafter PW, the sources of cosmic rays are located in the spiral arms of the galaxy (hereafter called region S) from which they can slowly leak out into an outer containment volume (hereafter called region H) which comprises part of the disk, and surrounding halo. The outer boundary of region H constitutes a closed box from which cosmic rays can not escape. Depletion of cosmic rays

in region H is due solely to nuclear interactions and energy losses. Region H thus contains an 'old component' and Region S contain a 'young component' of cosmic rays. The old component also permeates region S. A schematic picture of the closed galaxy model is shown inset in Figure 2.

The density of the young component of protons, γ_p ($\text{cm}^{-3} \text{GeV}^{-1}$), is simply:

$$\gamma_p = S_p t_s / V_S \quad (1)$$

where S_p is the rate of production of cosmic ray protons integrated over the galaxy ($\text{GeV}^{-1} \text{s}^{-1}$), t_s is the residence time (s) of protons in region S and is equal to the mean escape time for protons leaking from region S into region H. V_S is the total volume (cm^3) occupied by region S.

The density of the old component of protons, η_p , is given by:

$$\eta_p \approx f S_p t_{at} / V_H \quad (2)$$

where $f S_p$ is the rate of production of cosmic ray nucleons (bound and unbound) integrated over the galaxy (the assumption is that most nuclei leaking out of region S will fragment into nucleons in region H). We will use $f \approx (1 + 4 S_{\text{He}}/S_p) \approx 1.15$. t_{at} is the mean attenuation time of protons due to nuclear interactions in region H, and V_H is the total volume occupied by region H. Equation (2) is only valid if t_{at} is significantly less than the age of the galaxy and if S_p is independent of time as will be discussed later.

We can define an escape length x_S (g/cm^2) and an attenuation length x_{at} (g/cm^2) as the amount of matter traversed by protons in region S in time t_s and by protons in region H in time t_{at} respectively. Hence, we may obtain the ratio of the old to young components:

$$\eta_p / \gamma_p \approx \frac{f x_{at}}{(K-1)x_S} \quad (3)$$

where K is the ratio of the total mass of interstellar gas in the galaxy to that in region S.

The proton energy, E , remaining after suffering a nuclear interaction is on average about half its initial energy E' . The distribution in energy may be approximated by (eg. Gaisser, 1974):

$$N(E)dE \approx dE/E'. \quad (4)$$

For a power law cosmic ray energy spectrum with differential exponent $-\gamma$, we then obtain:

$$x_{at} \approx \frac{\gamma}{\gamma-1} x_1 \quad (5)$$

where x_1 is the mean interaction length, $\langle m \rangle / \sigma_{p-ISM}^{inel}$. For an interstellar medium comprising 90% hydrogen and 10% helium nuclei by number, the mean mass, $\langle m \rangle$, is about 2.2×10^{-24} g, and mean inelastic cross section, σ_{p-ISM}^{inel} , about 3.5×10^{-26} cm². Thus for $\gamma \sim 2.5$ (as seen from equation 5 above, the exact value is not critical), we obtain $x_{at} \approx 105$ g/cm² of interstellar material.

PW found that the observed ratio of light to medium nuclei would be consistent with their model for values of K ranging from 50 to 500 and for an energy dependent escape length given approximately by:

$$x_s \approx 15 \rho^{-1/2} \text{ g/cm}^2 \quad (6)$$

for rigidities, ρ , greater than ~ 4 GV/c. Since the composition of cosmic rays heavier than protons is dominated by the young component (most old nuclei will have fragmented into nucleons in region H), we note that x_s is essentially identical to the mean escape length, x_e , derived using the leaky-box model. We therefore use the result of a more recent analysis by Protheroe, Ormes and Comstock (1981) using the leaky-box model:

$$x_s \approx \begin{cases} 7 \text{ g/cm}^2, & \rho \leq 4 \text{ GV/c} \\ 7(\frac{\rho}{4})^{-0.4} \text{ g/cm}^2, & \rho > 4 \text{ GV/c.} \end{cases} \quad (7)$$

We have used equations (3), (5) and (7) to decompose the observed proton spectrum into its young and old components. For the total proton spectrum, we have used the range of demodulated spectra from the work of Morfill, Volk and Lee (1976). This range of spectra is plotted as the shaded area in figure 2.

We also show the old component obtained as described above for values of K ranging from 50 to 500 and the young component for $K = 100$.

3. Antiproton Production

Having obtained the cosmic ray proton spectra in the two regions of the closed galaxy model, we proceed to calculate the rates of production of antiprotons in these two regions. First we must consider the production of antiprotons in high energy pp interactions.

It is convenient to describe the inclusive reaction, $p + p \rightarrow \bar{p} +$ 'anything', in terms of the CM energy squared, s , and the Feynman scaling variable, $x = 2p_t^*/\sqrt{s}$ (* refers to the CM system). Then, following Gaisser and Maurer (1973) we define a function F_{pp}^- in terms of the invariant cross section for the process, $E \frac{d^3\sigma}{dp^3}$

$$F_{pp}^-(x, s) = \frac{1}{\sigma_{pp}^{inel}} \int_0^{p_t^{max}} 2\pi p_t E \frac{d^3\sigma}{dp^3} dp_t, \quad (8)$$

where p_t^{max} is the maximum value of the transverse momentum, p_t , which is kinematically allowed for given values of x and s .

In the most recent results from Fermilab (Johnson et al., 1978), the invariant cross section at fixed values of p_t and the radial scaling variable, x_R , was found to be independent of s over the range of incident proton energies available at Fermilab. The radial scaling variable is defined by:

$$x_R = E^*/E_{max}^* \quad (9)$$

where E_{max}^* is the maximum energy in the CM system that is available to an individual antiproton and is given by (Taylor et al., 1976):

$$E_{max}^* \approx (s - 7.02)/2\sqrt{s} \text{ GeV}. \quad (10)$$

x_R is thus a function of x , s and p_t , except that $x_R \rightarrow |x|$ as $s \rightarrow \infty$.

The data of Johnson et al. (1978) are well fitted by a function of the

form:

$$E \frac{d^3g}{dp^3} = \frac{A(1-x_R)^n}{(1+p_t^2/b)^4} \quad (11)$$

with: $A = 1.9 \pm 0.4 \text{ mb/GeV}^2$; $n = 8.1 \pm 1.4$; and $b = 1.2 \pm 0.3 (\text{GeV}/c)^2$. In Figure 3 we plot the product, $\sigma_{pp}^{\text{inel}}(s) F_{pp}^-(x,s)$, obtained from these fits as a function of x for various values of s . We point out that the dependence on s at $x = 0$ extrapolated from the Fermilab data is consistent with that observed over the ISR energy range by Guettler et al. (1976) as well as with the low energy data as fitted by Gaisser and Maurer (1973). These ISR data may therefore not indicate a breakdown of scaling in the central region ($|x| \ll 1$), but instead that the Feynman scaling limit may not yet have been reached (see also Ellsworth, 1979).

The rate of production of antiprotons of energy E , per interstellar nucleon, $P(E)$, in cosmic ray nuclear interactions in the interstellar medium is given by:

$$P(E) = 2 \int_{E_{\text{min}}}^{\infty} M(E') N_p(E') \sigma_{pp}^{\text{inel}}(s') F_{pp}^-(x,s') \frac{c}{\beta_{\text{H}}} dE' \text{ GeV}^{-1} \text{ s}^{-1}. \quad (12)$$

Here, N_p is the density of cosmic ray protons ($\text{cm}^{-3} \text{ GeV}^{-1}$) and is either n_p (region H), or $(Y_p + n_p)$ (region S); E'_{min} is the minimum proton energy required to produce an antiproton of energy E ; s' is the square of the CM system energy, $2m_p(E' + m_p)$; and M is a correction factor to take into account p-He interactions (regions S and H), and α -H interactions (region S only). This factor has been discussed by Giler et al. (1977), and we use here values applicable to charged pion production from our earlier work (Protheroe, 1981b). The factor of 2 in equation (12) is to include the production of antineutrons which decay into antiprotons. We approximate x in equation (12) by (Gaisser and Maurer, 1973):

$$x \approx [(E^2 - m_p^2 - \langle p_t^2 \rangle)^{1/2} - E(1 - 4 m_p^2/s)^{1/2}] / m_p \quad (13)$$

where the mean square transverse momentum was obtained from the Johnson

et al. (1978) fits:

$$\langle p_t^2 \rangle \approx 0.59 \text{ (GeV/c)}^2. \quad (14)$$

The rates of production of antiprotons obtained as described above for the two regions of the closed galaxy model are plotted in Figure 4. For region H, we show the production rates expected for values of K ranging from 50 to 500.

For comparison with previous work, we have calculated the \bar{p}/p ratio for the leaky-box model with an escape length of 5 g/cm² of hydrogen and for a proton spectrum of the form $E^{-2.6}$:

$$\bar{p}/p \approx \frac{10 E^{2.6}}{m_p c} \int_{E_{\min}}^{\infty} E'^{-2.6} \sigma_{pp}^{\text{inel}}(s') F_{pp}(x, s') \frac{c}{P_H} dE'. \quad (15)$$

This is plotted in Figure 1 and found to be in good agreement with recent results (Szabelski et al., 1980; Tan and Ng, 1981).

4. Equilibrium Antiproton Spectrum

To obtain the equilibrium spectrum of antiprotons one must take into account, in addition to their rates of production and escape from the containment volume, the effects of ionization losses and energy losses due to nuclear interactions (equation 4). The equilibrium density of antiprotons of energy E, $N_{\bar{p}}(E)$, is then obtained from:

$$N_{\bar{p}} \cdot \left(\frac{1}{x_e} + \frac{1}{x_i} + \frac{1}{x_{an}} \right) - \frac{d}{dE} \left(\frac{dE}{dx} N_{\bar{p}} \right) = \frac{P}{m_p c} + \int_E^{\infty} \frac{N_{\bar{p}} dE'}{E' x_i} \quad (16)$$

where: x_e is the mean escape length (x_s for region S; ∞ for region H); x_i and x_{an} are the mean lengths for nuclear interaction and annihilation; and dE/dx is the rate of ionization energy loss (GeV per g/cm²). While measurements of the total inelastic cross section, $\sigma_{pp}^{\text{inel}}$, have been made up to ~ 100 GeV, the annihilation cross section has only been measured up to kinetic energies of ~ 6 GeV (Spencer and Edwards, 1970; Locken and Derrick, 1963;

Amaldi et al., 1966; Lynch et al., 1963; Brou, 1973; Bockmann et al., 1966; Ferbel et al., 1968). To obtain the annihilation and non-annihilation inelastic cross sections, $\sigma_{\bar{p}p}^{\text{an}}$ and $\sigma_{\bar{p}p}^{\text{i}}$, separately at higher energies, we shall adopt two different approaches. The first is to extrapolate the observed annihilation cross section to high energies using a $1/\beta^*$ dependence (black absorbing sphere model: Koba and Takeda, 1958). This gives $\sigma_{\bar{p}p}^{\text{an}} \approx 24/(1+2m_p/T)^{1/2}$ mb. The measured $\sigma_{\bar{p}p}^{\text{inel}}$ is then consistent with $\sigma_{\bar{p}p}^{\text{inel}} = (\sigma_{\bar{p}p}^{\text{an}} + \sigma_{\bar{p}p}^{\text{i}})$ with $\sigma_{\bar{p}p}^{\text{i}} \approx 10$ mb. The second approach is to assume $\sigma_{\bar{p}p}^{\text{i}} = \sigma_{\bar{p}p}^{\text{inel}}$ and to obtain $\sigma_{\bar{p}p}^{\text{an}}$ by subtracting $\sigma_{\bar{p}p}^{\text{i}}$ from $\sigma_{\bar{p}p}^{\text{inel}}$. This leads for the energy range of interest to $\sigma_{\bar{p}p}^{\text{i}} \approx (32 - 5T^{-1/2})$ mb and $\sigma_{\bar{p}p}^{\text{an}} \approx 36T^{-1/2}$ mb. This latter form for the annihilation cross section is also consistent with the available data and may be more consistent with expectations of quark models at high energies (T. K. Gaisser, private communication). To obtain the annihilation and interaction lengths, $\lambda = \langle m \rangle / \sigma_{\bar{p} - \text{ISM}}$, we assume $\sigma_{\bar{p} - \text{ISM}} \approx 1.07 \sigma_{\bar{p}p}$. The term involving the integral in equation (16) is to account for inelastic interactions in which the \bar{p} does not annihilate.

It should be pointed out that the steady state solutions used here (equations 2 and 16) are only valid if the attenuation time of protons in region H, t_{at} , and the interaction-annihilation time of antiprotons, $(1/x_i + 1/x_{\text{an}})^{-1} / (n_H m_p c)$, is much less than the age of the galaxy, t_{gal} . Also, the conditions in the galaxy (matter density, cosmic ray sources, etc.) should have changed little during this time. The first conditions are not met if the mean number density of interstellar nucleons, n_H , in region H is less than $\sim 3 \times 10^{-3} \text{ cm}^{-3}$. In this case, the predicted antiproton flux will be too high and should be taken as an upper limit.

Equation (16) has been solved for region S to yield the young component of the antiproton flux which is plotted in Figure 5. Note that this flux is identical to that predicted for the leaky-box model with mean escape length given by equation (7). For region H, the antiproton production rate, P , in equation (16) contains an additional term to account for leakage from region S into region H. This additional source is given by:

$$P_L(E) = \frac{m_p^c}{(K-1)x_s} Y_{\bar{p}}(E) \quad (17)$$

and is plotted in Figure 4 for the values of K considered here. Equation (16) has then been solved for region H to yield the old component of antiproton flux and this is plotted in Figure 5 for values of K ranging from 50 to 500. We show the effect here of using different extrapolations of σ_{pp}^{an} on the predicted flux for $K = 50$.

Since the young component of the antiproton flux is the same for all values of K (it is determined only by the proton spectrum in the spiral arms and the escape length), the variation of total \bar{p} flux with K is determined by the old component. From figure 4 we see that the production rate per nucleon is higher for low values of K . This is expected from our decomposition of the proton spectrum into its young and old components (Figure 2) described by equation (3). Thus in figure 5 we see also that for high values of K the old component of antiproton flux is lowest.

5. Conclusion

The \bar{p}/p ratio obtained by dividing the sum of the young and old components of the antiproton spectrum (given in Figure 5) by the 'demodulated proton spectrum' of Figure 2 is plotted in Figure 6 for different values of K , together with the prediction for the leaky-box model. The decrease with energy at high

energies of the \bar{p}/p ratio for the leaky box model is due to our use of an energy dependent escape length. The prediction of Stephens (1981) is also shown for the closed galaxy model of Rasmussen and Peters (1975). The \bar{p} flux predicted for this model is equivalent to the old component of the flux in the PW model for $K = 1$ (it is interesting to note that our leaky box model prediction is equivalent to $K \rightarrow \infty$ in the PW model). Stephens' prediction for the leaky box model with energy dependent escape (not shown) is also consistent with our result. We compare these predictions with the observed ratios in the figure. The high energy data (Golden et al., 1979; Bogomolov et al., 1979) are found to be consistent with the predictions of the closed galaxy model for the same range of K that is required to reproduce the observed ratio of light to medium nuclei in the cosmic rays. Other aspects of this model should therefore be examined in detail (eg. positrons, γ -rays, ratio of light to medium nuclei at high energies). Such a study has already been undertaken for the case of positrons (Protheroe, 1981). From this work, it was found that the predicted positron flux for the closed galaxy model with $K = 100$ was consistent with the present data provided the interstellar density in region H, n_H , was less than ~ 0.3 nucleons/cm³. Attempts should also be made to put the model on a more sound theoretical basis by seeking a feasible mechanism to 'close the galaxy' to cosmic rays, at least up to ~ 100 GeV.

The low energy data (Buffington et al., 1981) are more difficult to fit by secondary antiproton production. In Figure 6 we also show the effect of solar modulation on the \bar{p}/p ratio for $K = 50$. For this, we have assumed that the modulation at the near solar maximum conditions when the observations were made may be described by a mean energy loss of 600 MeV (Urch and Gleeson, 1973). The observed ratio is still more than a factor of 10 (3.5 standard deviations) above the prediction.

An alternative explanation in terms of a primary antiproton component (Gaisser and Levy, 1974; Stecker, 1981) should not be discounted. If the leaky box model with an energy dependent mean escape length (equation 7) is a better description of the real situation than the closed galaxy model, then a primary antiproton component of magnitude $\sim 3 \times 10^{-4}$ of the observed proton spectrum would exist. This possibility is discussed further by Stecker, Protheroe and Kazanas (1981).

Acknowledgements

We are grateful to Drs. J. F. Ormes, V. K. Balasubrahmanyam, R. E. Streitmatter and T. K. Gaisser for stimulating discussions and for reading the manuscript.

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Figure Captions:

- Figure 1: Predictions of \bar{p}/p ratio by Gaisser and Maurer (1973) and later authors for leaky-box model with mean escape length of 5 g/cm^2 of hydrogen independent of energy and for a proton spectrum proportional to $E^{-2.6}$. Observations of Golden et al. (1979) (\odot), Bogomolov et al. (1979) (\circ) and Buffington et al. (1981) (\blacksquare) are indicated.
- Figure 2: The observed proton spectrum as decomposed into its young and old components for different values of K . Shown inset is a schematic representation of the regions of the galaxy in the closed galaxy model (not to scale).
- Figure 3: The dependence of $\sigma_{pp}^{\text{inel}} F_{\bar{p}}^{\text{pp}}$ (equation 8) on x for various values of s .
- Figure 4: The rates of production of antiprotons in regions S and H as a function of kinetic energy. Note that production rate for region S is identical to that for leaky box model. The source term due to leakage from region S into region H (equation 17) is also shown.
- Figure 5: Predicted young and old components of antiproton flux.
- Figure 6: Predicted \bar{p}/p ratio for leaky-box model with energy dependent escape and the closed galaxy model of Peters and Westergaard for various values of K . The dashed line is the prediction of Stephens (1981b) for the earlier closed galaxy model of Rasmussen and Peters. The effect of solar modulation on the prediction for $K = 50$ is shown by the curve labelled $K = 50$ (mod.). See Figure 1 for key to data and Figure 5 for key to annihilation cross section used.

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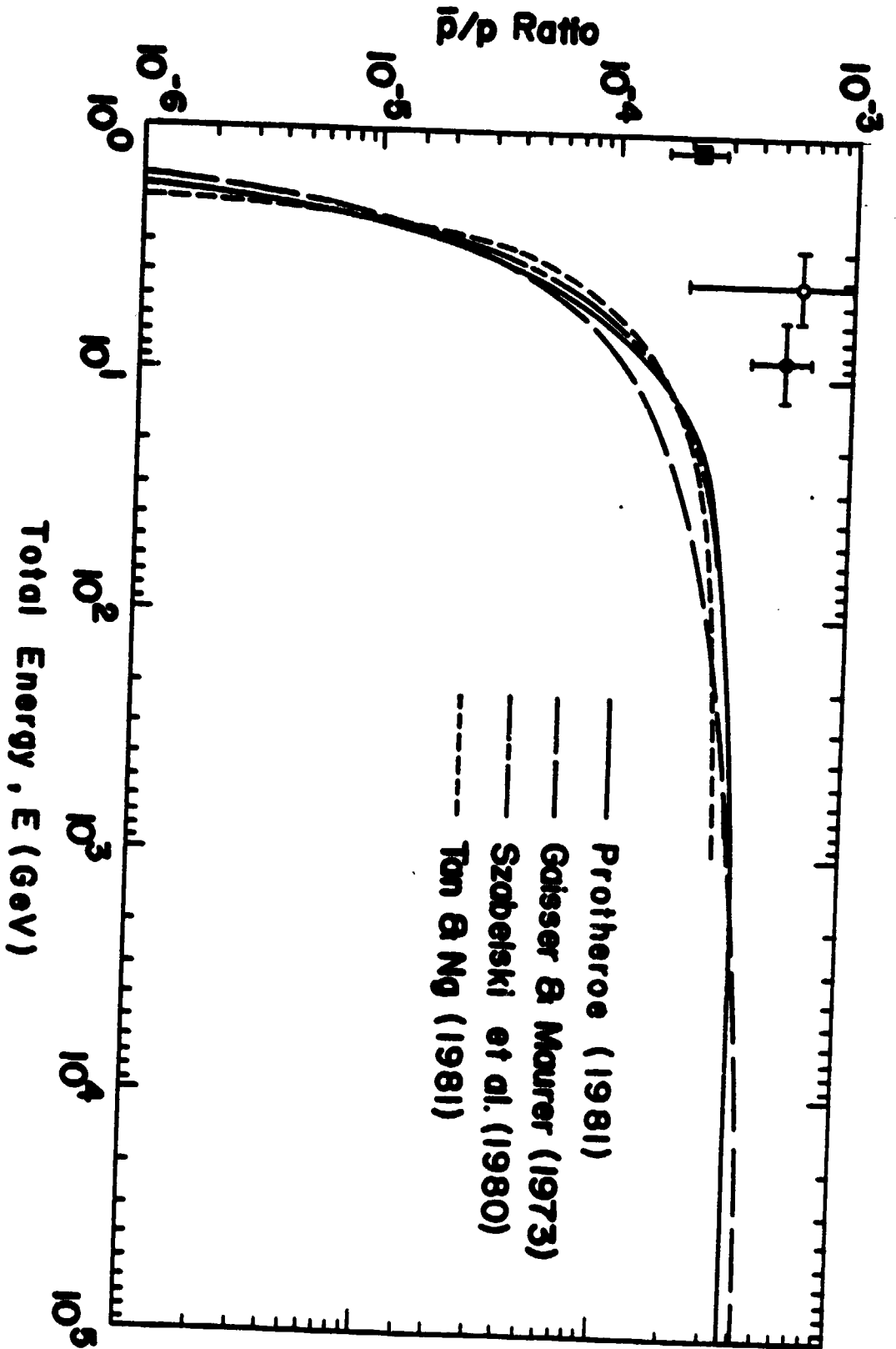


Figure 1

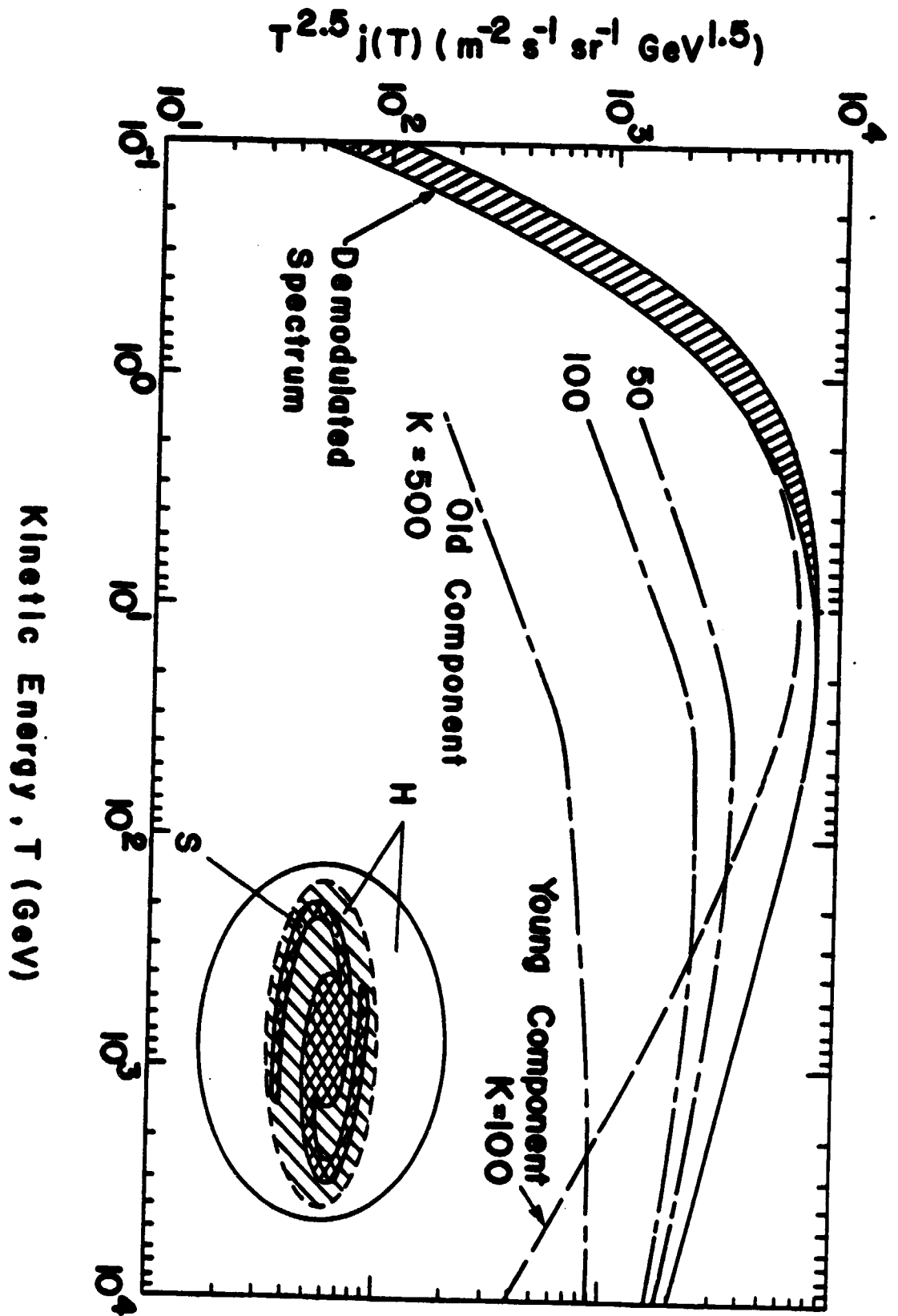


Figure 2

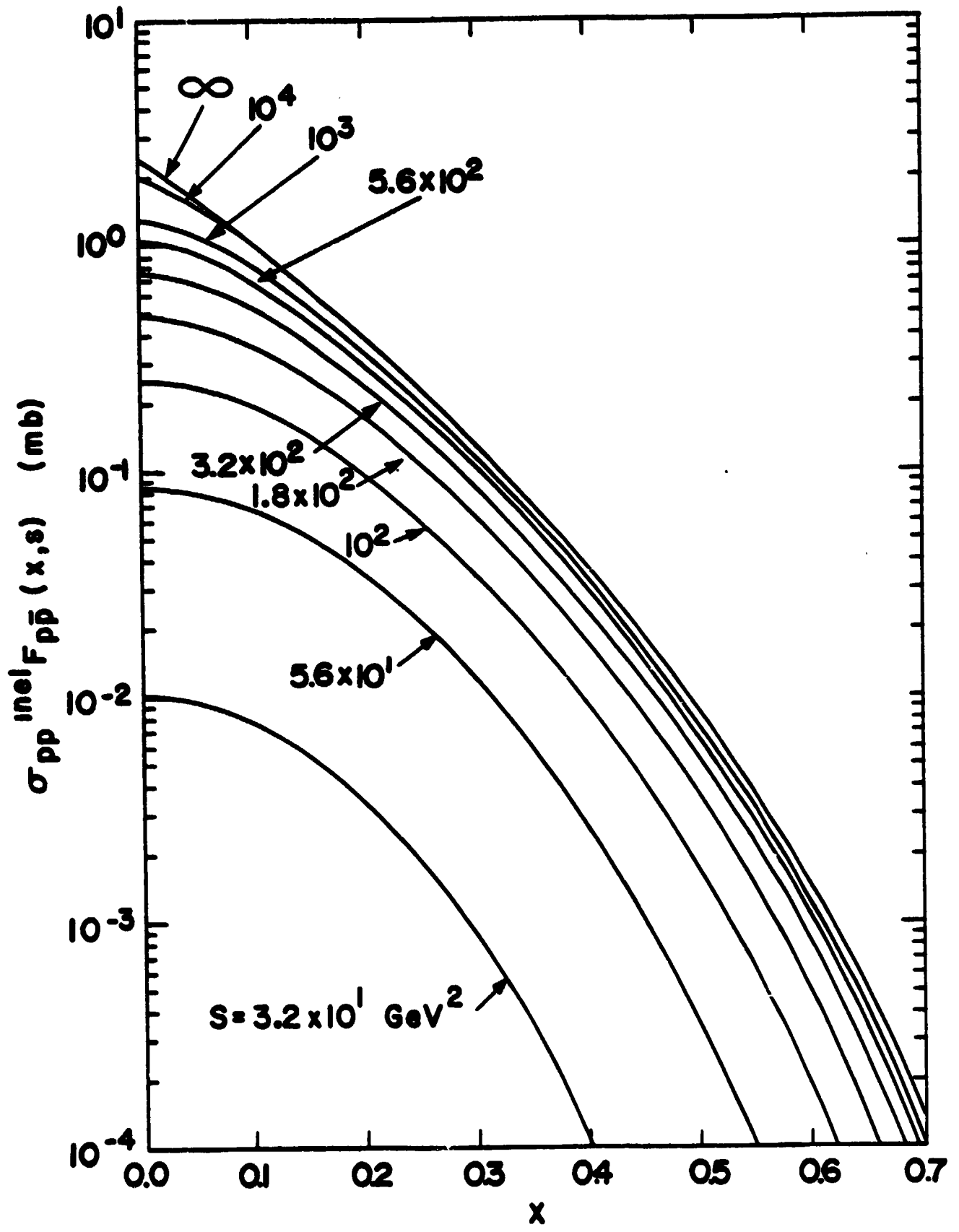


Figure 3

$T^{2.5} P(T)/4\pi [\text{GeV}^{1.5} (\text{s sr interstellar nucleon})^{-1}]$

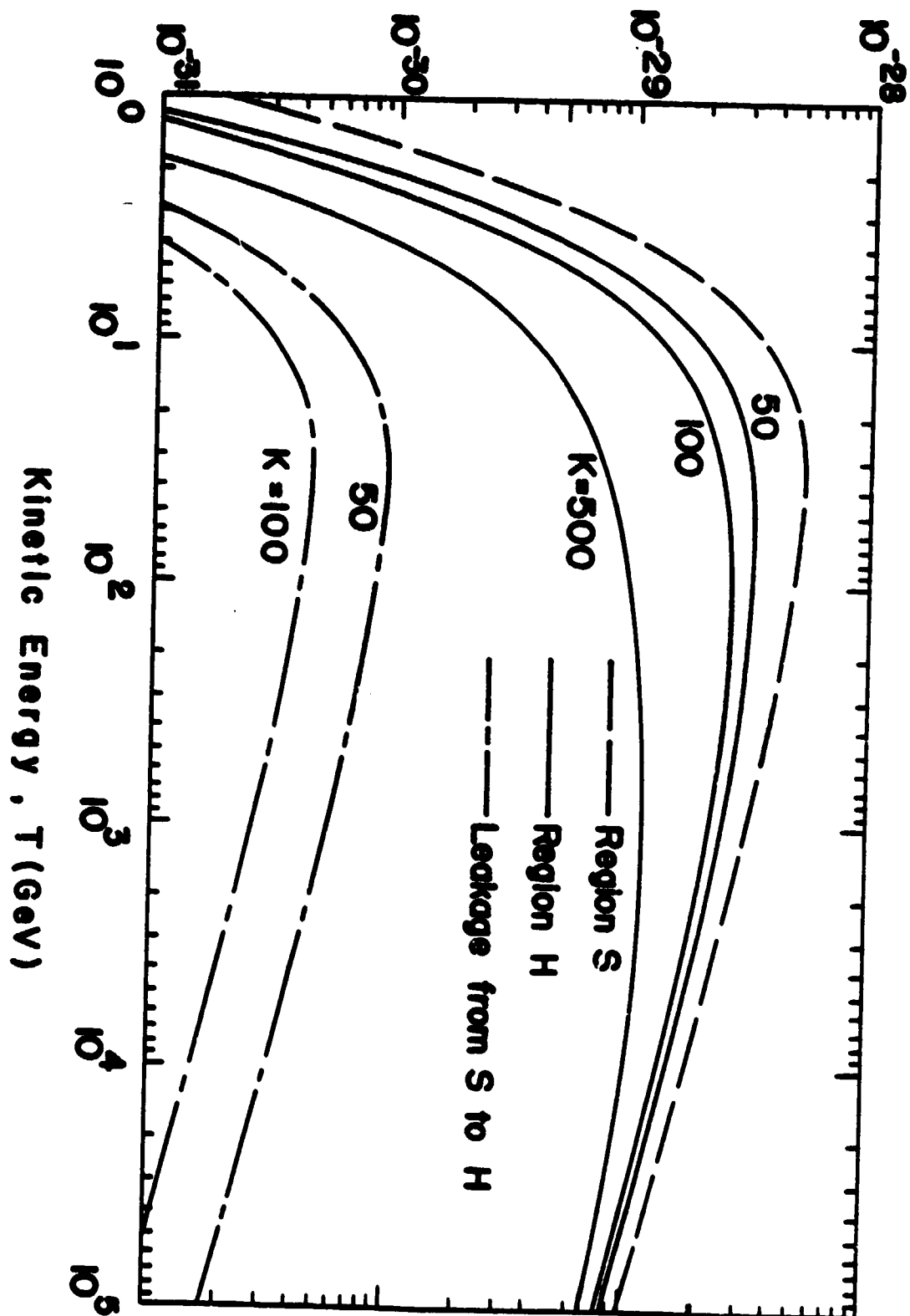


Figure 4

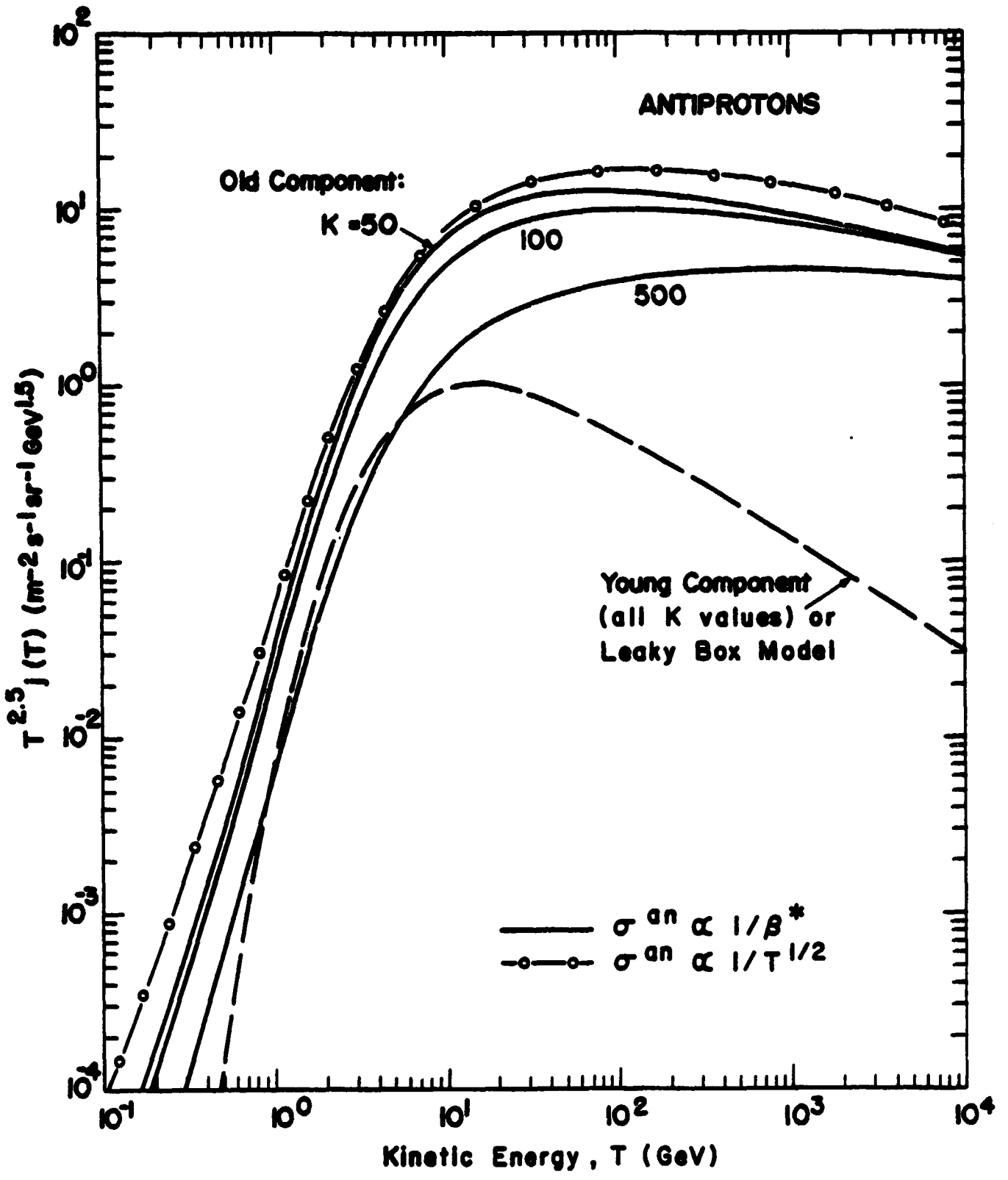


Figure 5

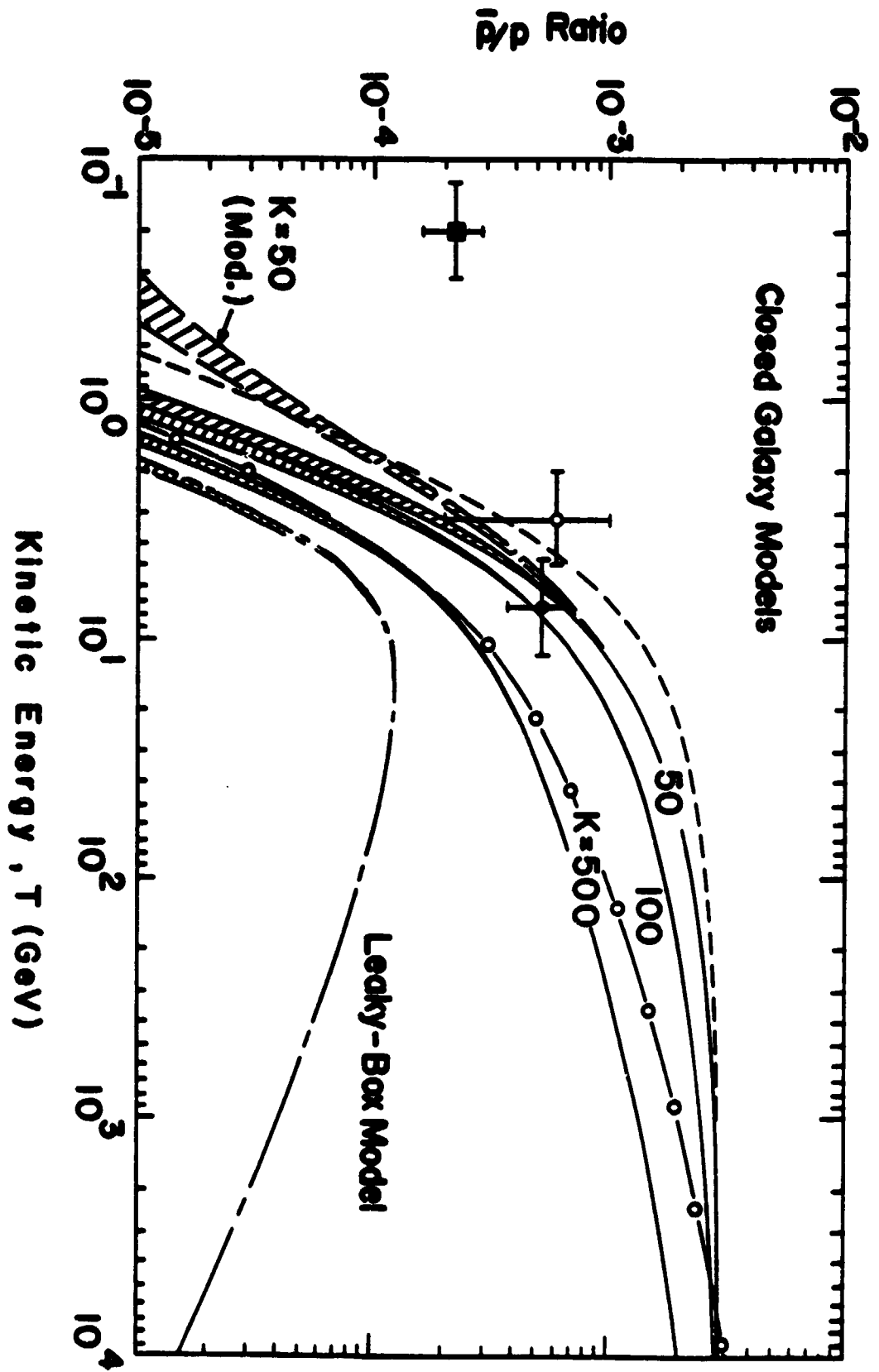


Figure 6