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ON THE NATURE OF THE COSMIC RAY POSITRON SPECTRUM

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Abstract

We have made a new calculation of the flux of secondary positrons above 100 MeV expected for various propagation models. The models investigated are the leaky box or homogeneous model, a disk-halo diffusion model, a dynamical halo model and the closed galaxy model. The parameters of these models have, in each case, been adjusted for agreement with the observed secondary/primary ratios and ^{10}Be abundance. The positron flux predicted for these models is compared with the available data. The possibility of a primary positron component is considered.

Subject Headings: Cosmic rays: abundances--galaxies: Milky Way--galaxies: structure

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INTRODUCTION

Low energy positrons are expected to be produced by the decay of radioactive isotopes created by nucleosynthesis in supernovae (e.q., Colgate, 1970) and possibly by pair production near the surface of pulsars (Sturrock, 1971). The bulk of the cosmic ray positrons observed above 100 MeV are, however, thought to be of secondary origin, resulting from the decay of π^+ produced in nuclear interactions of cosmic rays in the interstellar medium. Observations of high energy cosmic ray positrons, when combined with model predictions may thus help us understand the propagation of cosmic rays in the galaxy. Previous calculations of the production rate of positrons from this source have differed by as much as 50 percent resulting in diverse conclusions regarding propagation. In the present paper, we give the results of a new calculation of the positron production rate and estimate the flux of cosmic ray positrons expected for various propagation models.

MODELS FOR COSMIC RAY PROPAGATION

The propagation models we will consider include the widely used leaky-box model, a conventional diffusion model, the dynamical halo model and the closed galaxy model. In each case the model parameters are adjusted so that the predicted energy dependence of the boron/carbon ratio and the surviving fraction of the radioactive nuclide ^{10}Be are consistent with observation. Other propagation models will be briefly discussed.

a) Leaky Box or Homogeneous Models

These models are characterized by an exponential distribution of cosmic ray ages with mean lifetime, $\langle t \rangle$, which is related to the mean escape length or 'grammage', λ_e, by

$$\langle t \rangle = \lambda_e / \rho \beta c \quad (1)$$

where ρ is the mean density of interstellar material as sampled by the cosmic rays. From boron/carbon and other secondary to primary ratios, Protheroe, Ormes and Comstock (1981) found that $\lambda_e \approx 7$ g/cm^2 at rigidities, R, less than ~ 4 GV/c and $\lambda_e \approx 7(R/4)^{-0.4\pm0.1}$ g/cm^2 above 4 GV/c. Recent satellite measurements of the abundances of isotopes of Be by Wiedenbeck and Greiner (1980) indicate that ~ 29 percent of ^{10}Be survives decay at interstellar energies of a few hundred MeV/nucleon. From this surviving fraction, Wiedenbeck and Greiner conclude that $\langle t \rangle \approx (8.4^{+4.0}_{-2.4}) \times 10^6$ years for relativistic particles. For a mean escape length of 7 g/cm^2 of interstellar matter (90 percent hydrogen and 10 percent helium by number) this corresponds to a mean density of interstellar nuclei, n, of $(0.40^{+0.16}_{-0.13})$ atoms/cm^3.

b) Diffusive Halo Model

In this model, cosmic ray sources and matter are located in a disk of thickness 2a, which is surrounded by a halo of thickness 2D. Cosmic rays diffuse throughout the disk and the halo and escape freely from the boundary of the halo (Prischep and Ptuskin, 1975). We adopt a one dimensional approximation similar to that of Owens and Jokipii (1977a), and assume that the diffusion coefficient in the halo has the same value as that in the disk. From Freedman et al. (1980), we find that the diffusion coefficient, κ, is proportional to β/λ_e, the constant of proportionality depending on the values of a, D and the matter density in the disk. We adopt a $\approx$ 100 pc, comparable to the half thickness of the total hydrogen, i.e., $n(HI) + 2n(H_2)$, layer and a density of 1.1 atoms/cm^3 corresponding to a hydrogen surface density of 5.0 $M_\odot/pc^2$, the local value (Gordon and Burton, 1976). For an interstelar medium containing 10 percent He by number, this corresponds to a surface density of 7.2 $M_\odot/pc^2$. The halo is assumed to be devoid of matter. Since $\lambda_e \approx 7$ g/cm^2 at low energies, we can obtain values of the diffusion coefficent, κ, which would result in this grammage for different values of the halo thickness, D. This relationship may then be combined with the observed surviving fraction of ^{10}Be, f_s, to fix both D and κ in this model. Using formulae of Freedman et al. (1980) and $f_s \approx 0.29 \pm 0.08$ (Wiedenbeck and Greiner, 1980), we obtain $D = (1.7^{+2.0}_{-0.8})$ kpc and $\kappa/\beta = (1.6^{+1.9}_{-0.8}) \times 10^{28}$ cm^2/s (note that the errors in D and κ are not independent). This halo size is consistent with that obtained from an analysis of gamma ray data by Stecker and Jones (1977). Above a rigidity of 4 GV/c we adopt $\kappa/\beta = 1.6 \times 10^{28} (R/4)^{0.4}$ cm^2/s.

c) Dynamical Halo Model

This model is similar to the diffusive halo model described previously except that cosmic rays are convected outward in the halo by a galactic wind (Jokipii, 1976). The velocity of the scattering centers, or convection velocity, is assumed to be zero in the disk and a constant value, V, in the halo. Again, we assume that the value of the diffusion coefficient in the halo is the same as that in the disk. Because of the outward convection, a larger halo is required in this model to fit the observed values of λ_e and f_s than for a static halo. The surviving fraction of ^{10}Be in the dynamical halo model has been discussed by Owens and Jokipii (1977a), Jones (1979) and Freedman et al. (1980). Particles diffusing across the disk-halo boundary lose energy by shock deceleration and so λ_e and f_s depend on their energy spectrum in addition to the parameters of the propagation model. The motivation for this model comes from the observed energy dependence of the grammage. In this model, the diffusion coefficient may have a power law dependence on rigidity at all energies giving the observed decrease with energy above a few GeV/nucleon, but still give $\lambda_e \approx$ constant at low energies because of the galactic wind. Jones (1979) found that the form,

$$\kappa = \beta\kappa_0 R^{0.5} \qquad (2)$$

gave a good fit to the observed energy dependence of λ_e at high energies.

At low energies, if the cosmic ray injection spectrum of secondary nuclei had a differential power law exponent, of 2.5, the observed energy dependance of λ_e was also well fitted by this model for $VD/\kappa_0 = 1.4\ (GV/c)^{1/2}$ and $\rho ac/V = 20\ g/cm^2$. The observed spectrum at low energies is however more consistent with an injection spectrum of the form: $(T + 400\ MeV/nucleon)^{-2.6}$, where T is the kinetic energy per nucleon (Garcia-Munoz et al., 1977) rather than with $T^{-2.5}$. At a few hundred MeV/nucleon this spectrum is similar to the form $\beta T^{-\gamma}$ for $\gamma \sim 1.65$. Using the results of Freedman et al. (1980) for this value of γ, we find that better agreement with λ_e at low energies may be obtained with $\rho ac/V \approx 14.4\ g/cm^2$, or $V \approx 15.3$ km/s. To obtain D (and κ_0) we again use the observed surviving fraction of ^{10}Be. The formulae of Freedman et al. (1980) yield: $D = (4.0\ ^{+5.6}_{-2.2})$ kpc; $\kappa_0 = (1.3^{+1.8}_{-0.7}) \times 10^{28} cm^2/s$.

d) Closed Galaxy Model

Electrons and positrons have been considered in the closed galaxy model of Rasmussen and Peters (1975) by Badhwar and Stephens (1976), Ramaty and Westergaard (1976) and French and Osborne (1976). Problems with this model led to its revision by Peters and Westergaard (1977) and this is the model we shall consider here. The inability of conventional propagation models to explain the high cosmic ray antiproton flux observed at ~ 10 GeV (Golden et al., 1979) has led to a resurgence of interest in this model (Protheroe, 1981; Stephens, 1981). Secondary positrons in this model have been considered in an approximate way by Giler, Wdowczyk and Wolfendale (1977) and Stephens (1981).

In the closed galaxy model of Peters and Westergaard (1977) cosmic ray sources are located in the spiral arms of the galaxy. Cosmic rays are then partially trapped in the arms and leak out slowly into the surrounding halo, the outer boundary of which constitutes a closed box from which they cannot escape. Depletion of cosmic ray nuclei in the halo which contains low density interstellar matter is then due solely to nuclear interactions and energy losses. The halo thus contains an "old component" of cosmic rays consisting mainly of protons; heavier nuclei leaking from the arms spall into nucleons. In this model the Sun is located in a spiral arm and the cosmic rays we observe comprise a "young component" from the sources (these cosmic rays have not yet escaped from the arms) plus the old component which permeates the whole galaxy.

The parameters describing the closed galaxy model are K, the ratio of the mass of interstellar material in the galaxy as a whole to that in the spiral arms, and n_H, the number density of interstellar nuclei in the halo. We can decompose the observed proton spectrum into its young and old components for a given value of K, independent of n_H. This has been done by Protheroe (1981) for a leakage rate out of the arms which is consistent with the observed boron/carbon ratio.

e) Other Models

Secondary positrons have been considered by Stephens (1981) for the case of the nested leaky box model of Cowsik and Wilson (1973). In this model, cosmic ray sources are surrounded by dense regions of matter in which the cosmic rays are partially trapped before leaking out into an outer volume where the Sun is located. Escape from the source region is energy dependent, resulting in a variation of secondary to primary ratios with energy, while escape from the outer region is independent of energy. The effect of the matter surrounding the source is to produce a pathlength distribution which is deficient in short pathlengths when compared to an exponential (leaky box model) distribution. This results in the observed secondary to primary ratios (e.g., boron/carbon) being obtained for a lower mean escape length than for, e.g., leaky box models. With this lower mean escape length, the predicted flux of positrons will be lower than for models with an exponetial pathlength distribution, except at the very highest energies. This was indeed the result found by Stephens (1981). Other propagation models with a deficiency of short pathlengths, e.g., the 'no near sources model' (Lezniak and Webber; 1979) will also result in lower positron fluxes than in the leaky box model.

PROPAGATION OF POSITRONS

We have made a new calculation of the production spectrum of secondary positrons resulting from nuclear interactions of cosmic rays in the interstellar medium. For the cosmic ray proton spectrum we have taken the range of demodulated spectra from the work of Morfill, Völk and Lee (1976). First, we calculated the production rate of π^+ using fits to the inclusive cross section data on π^+ production in pp collisions surveyed by Taylor et al. (1976) and supplemented by low energy data of Blobel et al. (1974) and more recent high energy data of Guettler et al. (1976) and Johnson et al. (1978). Nuclear interactions involving He, either in the cosmic rays or in interstellar matter (assumed to be 10 percent by number), were taken account of as described by Giler, Wdowczyk and Wolfendale (1977) using emulsion data of Andersson, Otterlund and Stenlund (1979) to scale from pp to pHe interactions. The positron production spectrum was then obtained after a full treatment of pion and muon decays taking into account the muon decay asymmetry and positrons resulting from kaon production (Orth and Buffington, 1976). The production spectra obtained for π^+, μ^+ and e^+ are given in Figure 1 where the uncertainty at low energies due to uncertainties in the demodulation of the proton spectrum and at high energies due to uncertainty in the extrapolation with energy of the inclusive cross sections are indicated. The result for positrons is compared in Figure 2 with those obtained by previous authors and found to be in excellent agreement with that of Orth and Buffington (1976).

Energy losses by synchrotron radiation, inverse Compton interactions, bremsstrahlung and ionization are important in determining the shape of the positron energy spectrum for a given production spectrum. For synchrotron losses, we adopt an r.m.s. magnetic field strength of 6 microgauss, the value required to give consistency between the observed cosmic ray electron spectrum and the radio-synchrotron emission observed from the Galaxy (Rockstroh and Webber, 1978; Webber, Simpson and Cane, 1980). This <u>r.m.s.</u> value, is about twice as large as that usually adopted for the <u>mean</u> magnetic field strength. In addition to the 2.7^{o}K microwave background, we consider inverse Compton scattering off the far infra-red and optical radiation fields. The radiation densities we adopt for these fields are 0.47 eV/cm^3 and 0.46 eV/cm^3 corresponding to the local values in the model of Kniffen and Fichtel (1981) which is based on the infra-red survey by Boissé et al. (1981) and the stellar distributions of Bachall and Soneira (1980). These values lead to $\frac{dE}{dt}$ (Synch.+ Compton) ≈ 2.2×10^{-16} E^2 GeV/s. For ionization and bremsstrahlung losses we use formulae from Ginzburg and Syrovatskii (1964).

The flux of positrons in the leaky box model (exponential pathlength distribution) is given by:

$$j(E) = \frac{\rho c}{4\pi}\left(\frac{dE}{dt}\right)^{-1} \int_E^\infty dE' P_e(E') \exp\left\{-\int_E^{E'} \frac{dE''}{\langle t(E'')\rangle (dE/dt)}\right\} \qquad (3)$$

where $P_e(E)$ is the rate of production of positrons ($GeV^{-1} s^{-1} g^{-1}$), ρ is the density ($g\ cm^{-3}$), $\langle t(E)\rangle$ is the mean cosmic ray age at energy E, and (dE/dt) is the rate of energy loss from synchrotron, inverse Compton, bremsstrahlung and ionization.

In the Peters and Westergaard (1977) closed galaxy model, the positron flux is made up of two components. The young component is identical to the flux calculated for the leaky box model while the old component is obtained from equation (3) with $\langle t(E)\rangle \to \infty$. The rate of production of positrons in the halo depends on the old component of the proton spectrum. We have calculated this production rate (shown in Figure 1) for the old component of the proton spectrum obtained by Protheroe (1981) for K = 100. Peters and Westergaard (1977) found that this value of K was consistent with the observed secondary/primary ratios and it is also consistent with the high energy antiproton data (Protheroe, 1981). Since the rate of energy loss depends on density, the old component of positron flux will also depend on the density in the halo.

For the diffusion models, we have used the Monte Carlo technique described by Owens and Jokipii (1977b). Analytic treatments are available for specific cases of power law injection spectra (eg. Lerche and Schlickeiser, 1980). We have used the Monte Carlo technique as the injection spectrum of positrons (Figure 1) is not a power law, and because this method facilitates treatment of a break in the energy dependence of the diffusion coefficient.

OBSERVED SPECTRA

In order to reduce systematic differences between the various experiments, we shall compare our predictions with the observed $e^+/(e^++e^-)$ ratio rather than with the positron spectrum directly. We must therefore consider the total interstellar electron (e^+ and e^-) spectrum in some detail. Direct measurements have been made up to several hundred GeV; however, below ~ 10 GeV the electron spectrum observed directly differs considerably from the interstellar spectrum because of solar modulation. At low energies then the best estimates of the interstellar spectrum may come from radio observations of the galactic synchrotron emission. Tan and Ng (1981a) have however recently attempted a demodulation of the direct observations and find a local interstellar electron density which is about a factor of 10 lower at 100 MeV than the spectrum of Webber, Simpson and Cane (1980). This discrepancy will be discussed later. We show in Figure 3 a representative sample of the direct observations above ~ 5 GeV together with the interstellar spectrum at low energies inferred from radio data by Webber, Simpson and Cane (1980). The interstellar spectrum we adopt is shown as the solid line.

The $e^+/(e^++e^-)$ ratio obtained by dividing the predicted positron flux by the observed total electron flux (figure 3) is plotted in Figure 4(a) for the leaky-box, diffusive halo and dynamical halo models and in Figure 4(b) for the closed galaxy model (K=100) for various densities in the halo. The observed ratios are also given in these figures for comparison. The differences between the predictions shown in Figure 4(a) are small, and we cannot distinguish between these models with existing data. From 1 to 10 GeV, all the predictions except for the closed galaxy model with a high density in the halo ($\gtrsim 0.3\ cm^{-3}$) are consistent with the observations.

Below 1 GeV none of the predictions fits the observed ratio, however solar modulation must be considered before drawing conclusions. If the modulation is the same for e^+ and e^-, and the modulation can be approximated by the force field solution (Gleeson and Axford, 1968) then the observed ratios should be shifted to a higher energy corresponding to the observed energy plus the mean energy lost in the heliosphere, increasing the discrepancy. However, this simple picture of modulation may not be correct (Burger and Tanaka, 1970; Jokipii and Kopriva, 1979). In any case, demodulation of the data is unlikely to reduce the discrepancy unless positrons are modulated differently from electrons. If the cosmic ray electron density varies over distances of ~ 100 pc, then the local interstellar electron spectrum may be lower than that obtained from radio data. This has been suggested by Strong and Wolfendale (1978) and Tan and Ng (1981b) and may account for the discrepancy. Alternatively, the mean escape length of electrons or positrons may differ from that of nuclei (Giler, Wdowczyk and Wolfendale, 1977).

The models discussed earlier showing a deficiency of short pathlengths in the pathlength distribution, e.g., the nested leaky box model, give a lower positron flux in this energy range and hence give a worse fit to the data. Motivated by the high energy antiproton data (Golden et al., 1979), Cowsik and Gaisser (1981) have, however, suggested a modification to the nested leaky box model which can give enhanced antiproton production in the galaxy without affecting the secondary/primary ratios. This modification, which could be applied to most of the other propagation models as well, involves the addition of a set of cosmic ray sources shrouded with ~ 50 g/cm^2 of matter. Cosmic ray nuclei would interact on traversing the matter, producing pions, antiprotons, etc., and spall, eliminating the complex nuclei (i.e., those heavier than protons). The neutral pions would decay into gamma-rays; these additional sources are thus to be identified with the discrete galactic gamma-ray sources (Swanenburg et al., 1980). Positrons would result from the positive pions which are produced and may or may not contribute importantly to the cosmic ray positron flux depending on the strength of the magnetic fields associated with these sources. In any case, the energy spectrum of these additional positrons as seen at Earth would be steeper than for those produced in the interstellar medium because of energy losses both in the source region and on traversing the finite distances from the sources to the Earth. The addition of such a component may possibly improve the agreement between the predicted and observed fluxes at low energies.

Above 10 GeV the observed ratio lies above the predictions except for the closed galaxy models having a high matter density in the halo. The statistical errors for these data are however large, and new measurements are required before conclusions can be drawn about possible primary origin.

CONCLUSIONS

The production spectrum of secondary positrons has been calculated over the energy range 100 MeV to 1 TeV. Observations of the positron spectrum in this energy range should provide information about the propagation of cosmic rays in the galaxy and solar modulation. In particular, they may enable us to distinguish between the various propagation models that have been proposed.

With the present measurements of the $e^+/(e^+ + e^-)$ ratio, we are unable to distinguish between leaky box, diffusive halo and dynamical halo models. For progress at energies below a few GeV, a greater understanding of the solar modulation of electrons and positrons and the relationship between the local interstellar spectrum and the observed radio data is required. In addition, new experiments with higher exposure factors will be required as well as improved measurements of the boron/carbon ratio and ^{10}Be abundance to constrain the propagation models.

The data rule out a large primary positron component at high energies distributed uniformly throughout the Galaxy. A component as large as ~ 2 percent of the observed electron spectrum is, however, allowed within the present uncertainties. The observation of a gamma-ray line at 0.511 MeV (Leventhal, MacCullum and Stang, 1978) has been interpreted to indicate that low energy positrons are copiously produced in the galaxy (Ramaty and Lingenfelter, 1979). A primary positron component as large as a few percent could arise if only a small fraction of these were accelerated to high energies (Lingenfelter and Ramaty, 1979). Definitive statements about primary positrons must however await new measurements.

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REFERENCES

Andersson B., Otterlund, I. and Stenlund, E., 1979: Proc. 16th Int. Cosmic Ray Conf., Kyoto, 6, 182.

Bachall, J. N., and Soneira, R. M., 1980: Ap. J. Lett., 238, L17.

Badhwar, G. D., Golden, R. L., Brown, M. L., and Lacy, J. L. 1975: Astrophys. and Space Sci., 37, 283.

Badhwar, G. D., and Stephens, S. A., 1976: Phys. Rev. D, 14, 356.

Blobel, V., et al., 1974: Nucl. Phys., B69, 454.

Boissé, P., Gispert, R., Coron, N., Wijnbergen, J., Serra, G., Ryter, C., and Puget, J. L., 1981: Astron. Astrophys., 94, 265.

Buffington, A., Orth, C. D., and Smoot, G. F., 1975: Ap. J., 199, 669.

Burger, J. J. and Tanaka, Y., 1970: Ap. J., 162, 305.

Colgate, S. A., 1970: Astrophys. and Space Sci., 8, 457.

Cowsik, R., and Wilson, L. W., 1973: Proc. 13th Int. Cosmic Ray Conf., Denver, 1, 500.

Cowsik, R., and Gaisser, T. K., 1981: Proc. 17th Int. Cosmic Ray Conf., Paris 2, 218.

Daugherty, J. K., Hartman, R. C., and Schmidt, P. J., 1975: Ap. J., 198, 493.

Fanselow, J. L., Hartman, R. C., Hildebrand, R. H., and Meyer, P., 1969: Ap. J., 158, 771.

Freedman, I., Giler, M., Kearsey, S., and Osborne, J. L., 1980: Astron. Astrophys., 82, 110.

Freier, P. S., Gilman, C., and Waddington, C. J., 1977: Ap. J., 213, 588.

French, D. K., and Osborne, J. L., 1976: Nature, 260, 372.

Garcia-Munoz, M., Mason, G. M., and Simpson, J. A., 1977: Proc. 15th Int. Cosmic Ray Conf., Plovdiv, 1, 301.

Ginzburg, V. L., and Syrovatskii, S. I., 1964: "The Origin of Cosmic Rays", Macmillan Co., New York.

Giler, M., Wdowczyk, J., and Wolfendale, A. W., 1977: J. Phys. A., 10, 843.

Gleeson, L. J., and Axford, W. I., 1968: Ap. J., 154, 1011.

Golden, R. L., Horan, S., Manger, B. G., Badhwar, G. D., Lacy, J. L., Stephens, S. A., Daniel, R. R., and Zipse, J. E., 1979: Phys. Rev. Lett., 43, 1196.

Gordon, M. A., and Burton, W. B., 1976: Ap. J., 208, 346.

Guettler, K., et al., 1976: Phys. Lett., 64B, 111.

Hartman, R. C., and Pellerin, L. J., 1976: Ap. J., 204, 927.

Johnson, J. R., Kammerud, R., Ohsugi, T., Ritchie, D. J., Shafer, R., Theriot, D., Walker, J. K. and Taylor, F. E., 1978: Phys. Rev. D., 17, 1292.

Jokipii, J. R., 1976: Ap. J., 208, 900.

Jokipii, J. R., and Kopriva, D. A., 1979: Ap. J., 234, 381.

Jones, F. C., 1979: Ap. J., 229, 747.

Kniffen, D. A., and Fichtel, C. E., 1981: Ap. J. (in press).

Lerche, I. and Schlickeiser, R., 1980: Ap. J., 239, 1089.

Leventhal, M., MacCullum, C. J., and Stang, P. D., 1978: Ap. J. Lett., 225, L11.

Lezniak, J. A., and Webber, W. R., 1979: Astrophys. and Space Sci., 63, 35.

Lingenfelter, R. E. and Ramaty, R., 1979: Proc. 16th Int. Cosmic Ray Conf., Kyoto, 1, 501.

Meegan, C. A., and Earl, J. A., 1975: Ap. J., 197, 219.

Morfill, G. E., Volk, H. J., and Lee, M. A., 1976: J. Geophys. Res., 81, 5841.

Nishimura, J., et al., 1980: Ap. J., 238, 394.

Orth, C. D., and Buffington, A., 1976: Ap. J., 206, 312.

Owens, A. J., and Jokipii, J. R., 1977a: Ap. J., 215, 677.

Owens, A. J., and Jokipii, J. R., 1977b: Ap. J., 215, 685.

Peters, B., and Westergaard, N. J., 1977: Astrophys. and Space Sci., 48, 21.

Prince, T. A., 1979: Ap. J., 227, 676.

Prischep, V. L. and Ptuskin, V. S., 1975: Ap. and Space Sci., 32, 265.

Protheroe, R. J. Ormes, J. F., and Comstock, G. M., 1981: Ap. J., 247, 362.

Protheroe, R. J., 1981: Ap. J. (in the press).

Ramaty, R., 1974: in "High Energy Particles and Quanta in Astrophysics", eds: F. B. McDonald and C. E. Fichtel, MIT Press, Cambridge, MA.

Ramaty, R. and Lingenfelter, R. E., 1979: Nature, 278, 127.

Ramaty, R. and Westergaard, N. J., 1976: Astrophys. and Space Sci., 45, 143.

Rasmussen, I. L. and Peters, B., 1975: Nature, 258, 412.

Rockstroh, J. M., and Webber, W. R., 1978: Ap. J., 224, 677.

Stecker, F. W., and Jones, F. C., 1977: Ap. J., 217, 843.

Stephens, S. A., 1981: Nature, 289, 267.

Strong, A. W., and Wolfendale, A. W., 1978: J. Phys. Nucl. Phys., 4, 1793.

Sturrock, P. A., 1971: Ap. J., 164, 529.

Swanenburg, B. N., et al., 1981: Ap. J. Lett.

Tan, L. C., and Ng, L. K., 1981a: J. Phys. G., 7, 1123.

Tan, L. C., and Ng, L. K., 1981b: J. Phys. G., 7, 1135.

Taylor, F. E., et al. 1976: Phys. Rev. D., 14, 1217.

Webber, W. R., Simpson, G. A., and Cane, H. V., 1980: Ap. J., 236, 448.

Wiedenbeck, M. E., and Greiner, D. E., 1980: Ap. J. Lett., 239, L139.

Figure Captions

Figure 1: Production rates of π^+, μ^+, and e^+ per interstellar nucleon in the disk of the galaxy. Uncertainties associated with the demodulation of the cosmic ray proton spectrum and with extrapolation of cross sections to high energies are indicated by hatching. In addition, the production spectra are uncertain by at most a further 15 percent due to uncertainties in the tranverse momentum distribution of pions produced in pp interactions. Also shown, e^+ (old component), is the production rate of positrons in the halo of the closed galaxy model for K=100.

Figure 2: Production rate of e^+ per gram of interstellar matter from the present work is compared with previous results. For other references to earlier work, see Orth and Buffington (1976).

Figure 3: A representative sample of electron spectrum measurements. The cosmic ray electron spectrum used in the present work is indicated (solid line).

Figure 4: Comparison of observed $e^+/(e^++e^-)$ ratio with those obtained by dividing predicted e^+ flux by observed $(e^+ + e^-)$ flux for: (a) leaky box, diffusive halo and dynamical halo models; (b) closed galaxy model (K=100) for various densities of neutral matter in the halo (dashed line for ionized matter). Data are from: Buffington, Orth and Smoot (1975) (■); Daugherty, Hartman and Schmidt (1975) (●); Fanselow, et al. (1969) (□); Hartman and Pellerin (1976) (○). The error bar attached to the prediction for the diffusive halo model indicates the precision of our Monte Carlo calculations.

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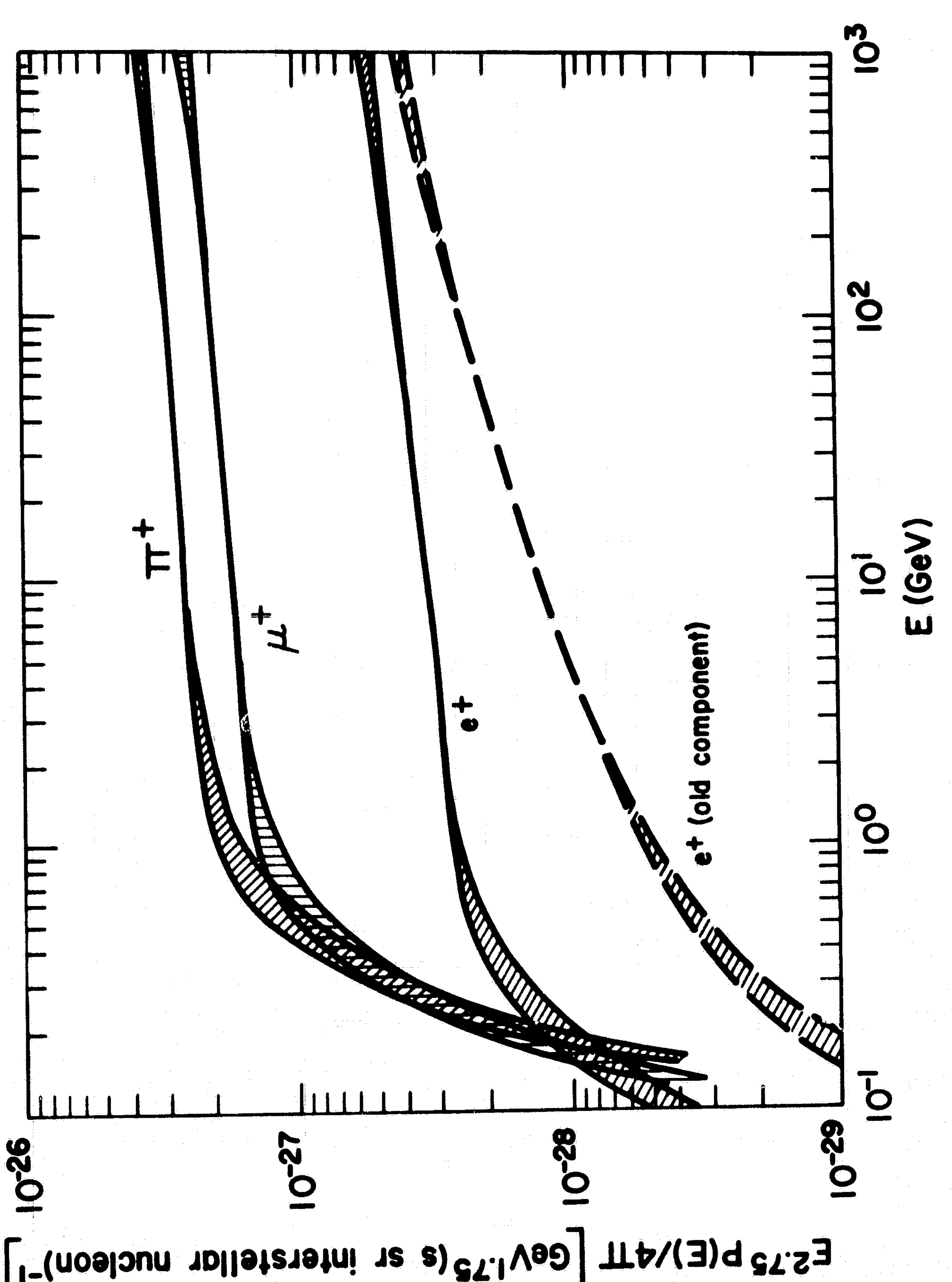
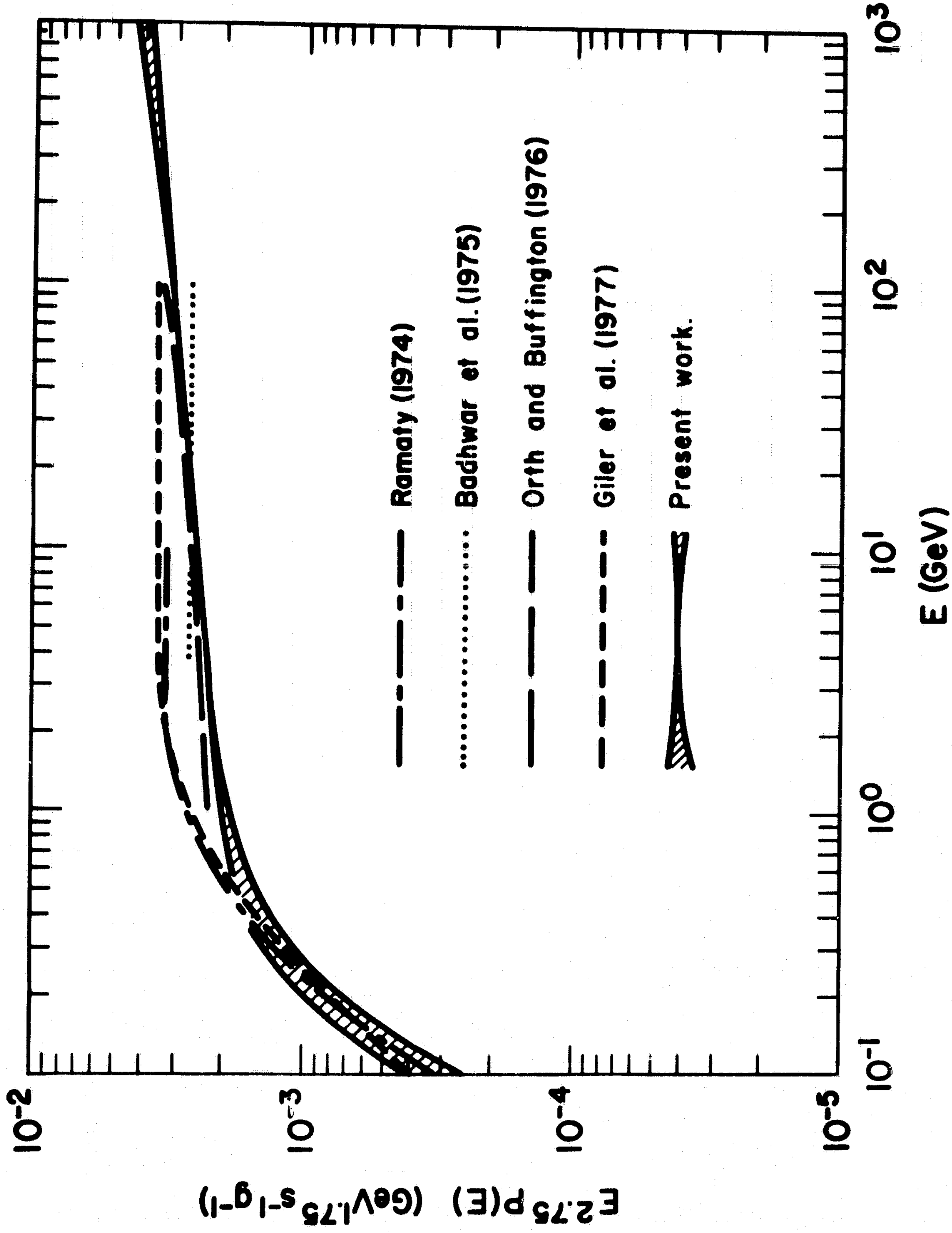


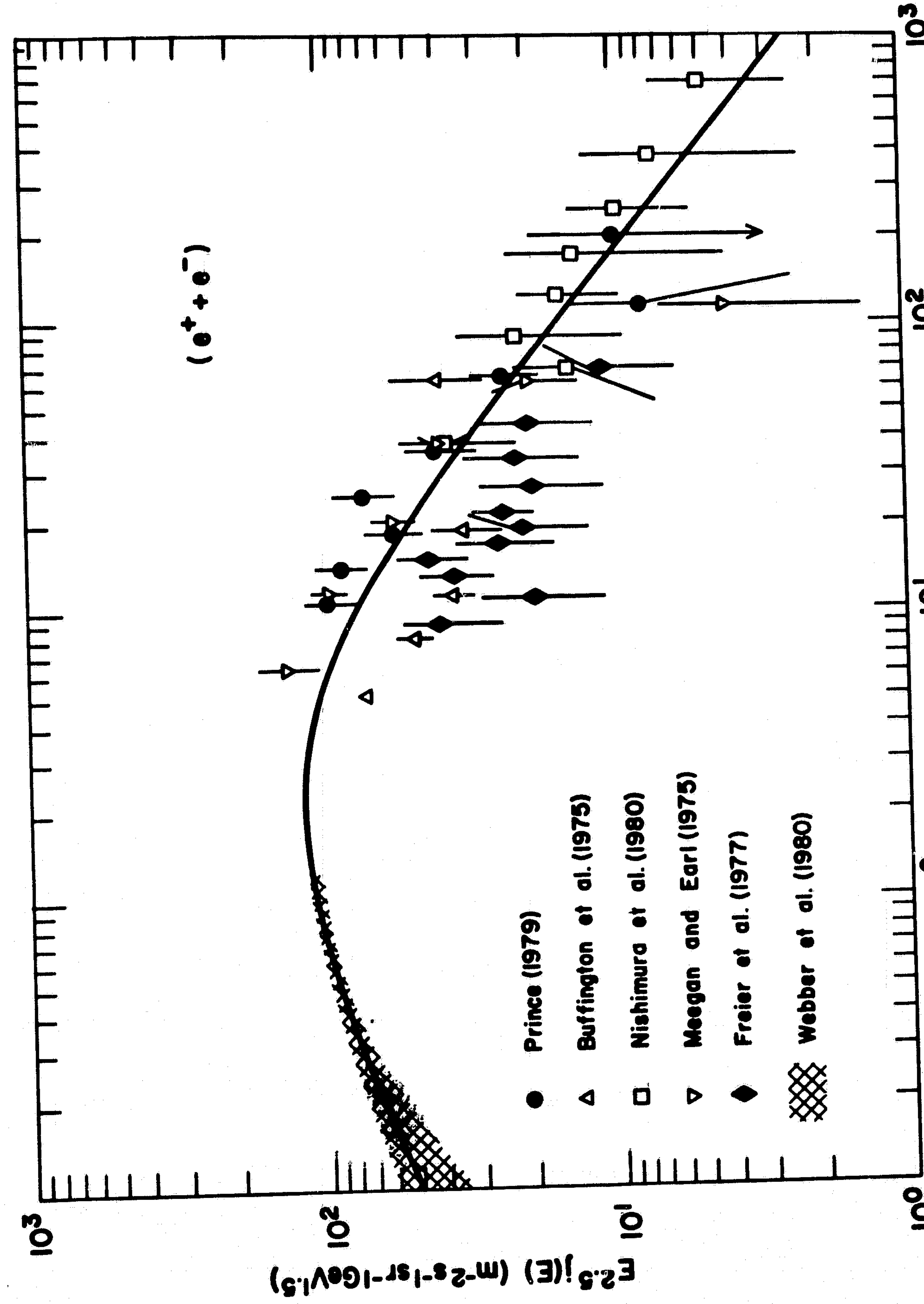
E^2.75 P(E)/4π [GeV^1.75 (s sr interstellar nucleon)^-1]
10^-26
10^-27
10^-28
10^-29
10^-1
10^0
10^1
10^2
10^3
E (GeV)
π+
μ+
e+
e+ (old component)

Figure 1



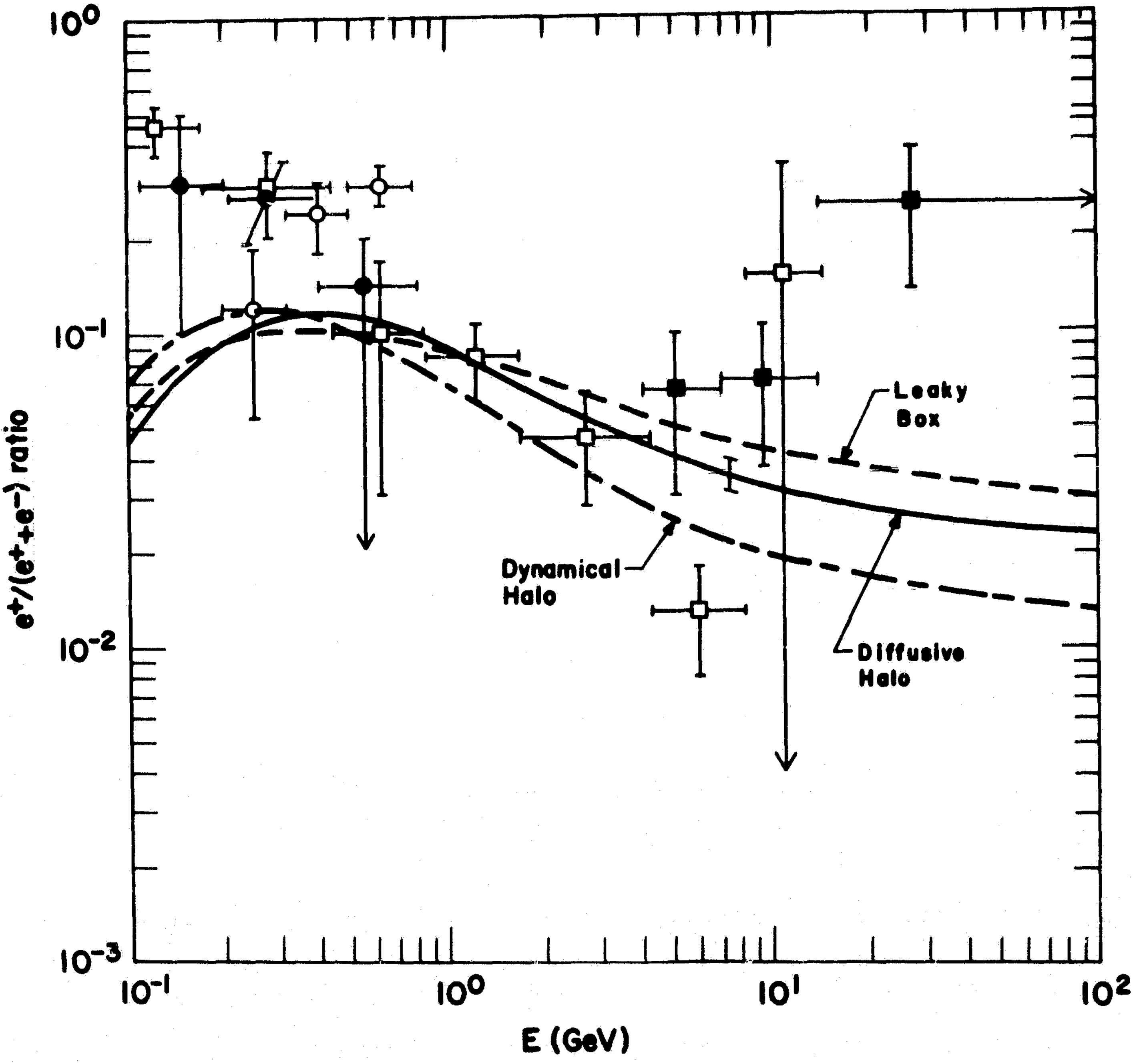
Ramaty (1974)
Badhwar et al. (1975)
Orth and Buffington (1976)
Giler et al. (1977)
Present work.
E (GeV)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$E^{2.75}$ p(E) (GeV$^{1.75}$ s^{-1} g^{-1})

Figure 2



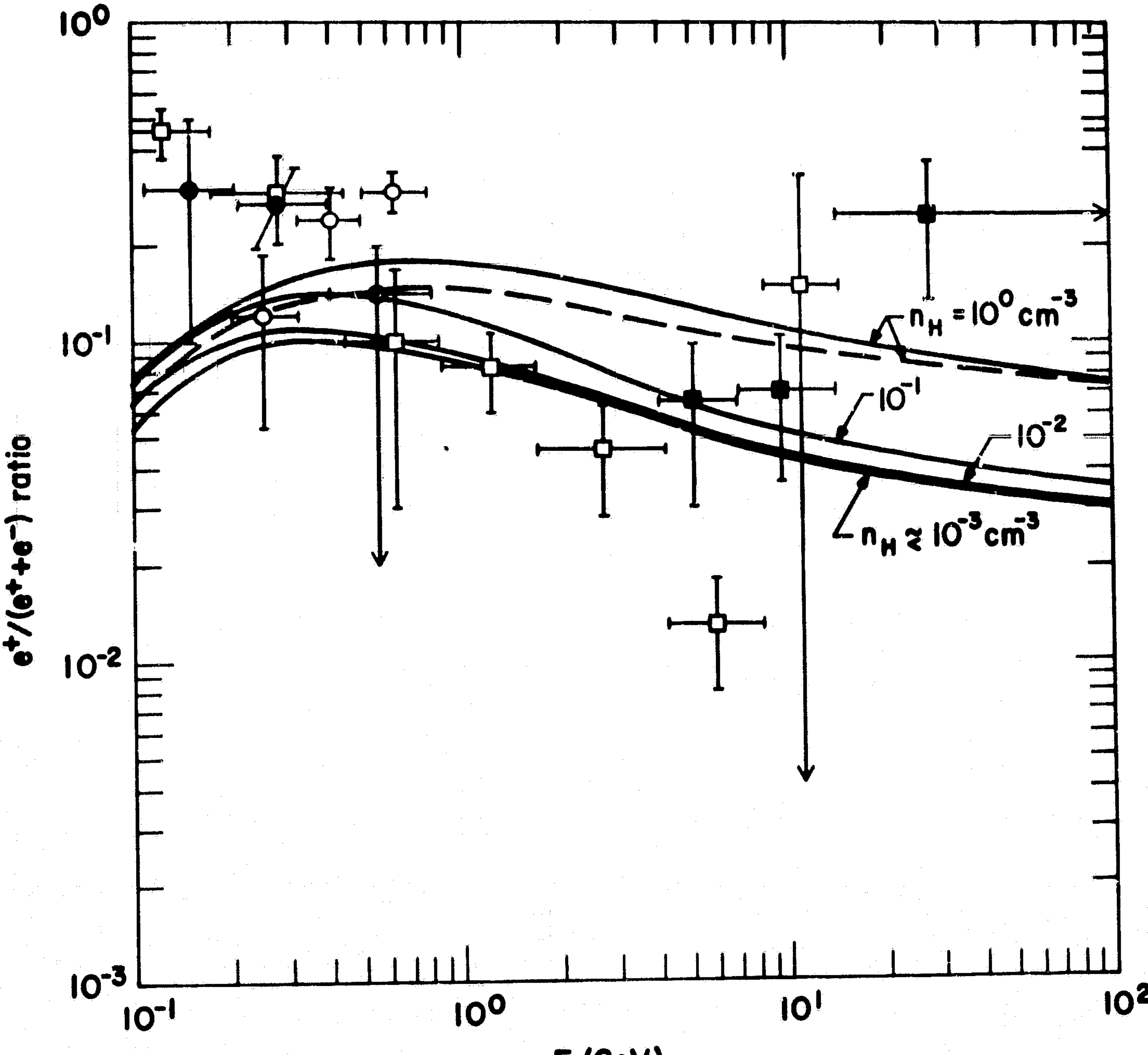
(e⁺ + e⁻)
Prince (1979)
Buffington et al. (1975)
Nishimura et al. (1980)
Meegan and Earl (1975)
Freier et al. (1977)
Webber et al. (1980)
E (GeV)
E^2.5 j(E) (m^-2 s^-1 sr^-1 GeV^1.5)

Figure 3



10^0
10^{-1}
10^{-2}
10^{-3}
$e^+/(e^++e^-)$ ratio
Leaky Box
Dynamical Halo
Diffusive Halo
10^{-1}
10^0
10^1
10^2
E (GeV)

Figure 4(a)



10^0
10^-1
10^-2
10^-3
e^+/(e^+ + e^-) ratio
n_H = 10^0 cm^-3
10^-1
10^-2
n_H ≲ 10^-3 cm^-3
10^-1
10^0
10^1
10^2
E (GeV)

Figure 4(b)