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Calculations of >1 GeV Electrons in the Galaxy Using a Monte Carlo Diffusion Program – A Comparison with Experiment

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Abstract

We employ a Monte Carlo diffusion model to study the propagation of electrons in the Galaxy. The parameters governing the diffusion, the boundary distance (halo size) and the matter density are determined from the application of this same program to the propagation of cosmic ray protons and nuclei including radioactive ones. The electrons are most sensitive to the interstellar B field and to the source spectral index. If we concentrate on the energy range above 1 GeV, we find that the average interstellar B field is constrained to be between 4-6 μG, and the electron source spectral index is between -2.3 and -2.4. These limits on B and on the electron source spectral index are compared with those from a similar analysis of low energy electrons presented in a companion paper.

1. Introduction

We employ a Monte Carlo diffusion model to study the propagation of electrons in the Galaxy. In this paper we examine their interstellar (IS) spectrum above 1 GeV and compare the calculations with experiment. The propagation parameters governing the diffusion, the boundary distance (halo size) and the matter density are best determined from a study of nuclei propagation and are derived from the application of this same program to the propagation of protons and nuclei including radioactive ones (Webber, 1999). Specifically we find from that study: 1) the diffusion coefficient is given by $K(P) = 2x10^{28}P^{0.5}$ $cm^2 sec^{-1}$ above 1 GV; 2) the halo size, $\pm z_B$=3kpc; 3) the line integral of the matter density $I_m = \int n\cdot dz = 8.5x10^{20}$ cm^{-2} where n_0=1.2 cm^{-3} and the z dependence of the matter density ($H_1+H_2+H_{II}$) is described by $\exp^{-Z}/z_m$ where z_m=0.2 kpc. Of the remaining parameters used to describe the propagation, the electrons are most sensitive to the interstellar B field and to the source spectral index.

2. Calculations and Comparison with Measurements

For the B field in the z direction we assume $B=B_0 \exp^{-Z}/z_B$ where z_B=1.5 kpc. The energy loss by synchrotron radiation is described by $dE/dt=-b_s \cdot E^2$ where b_s= 2.5 x 10^{-16} sec^{-1} (B_0=6μG). The inverse Compton energy loss is described by $dE/dt=-b_{IC} \cdot E^2$ where the value of $b_{IC}=0.5x10^{-16}$ sec^{-1}, accounts for the losses due to visible, IR and CMB photons. The z dependence of the photon field is taken to be $h\nu=h\nu_0 \exp^{-Z}/z_{h\upsilon}$ where $z_{h\upsilon}$=3 kpc. The energy loss by bremsstrahlung and by ionization are determined from the matter distribution described above. The Monte Carlo calculation is described more completely in Webber and Rockstroh, 1997. For the calculations discussed here 10^4 particles are injected uniformly in time in each of 48 logarithmically spaced intervals, 8 to the decade, from 10 MeV to 10^4 GeV. The resulting final distribution of particles is binned in both the z dimension and in time as well as energy. The total integration time is > the characteristic diffusion time, R^2_B/K, to the boundary for all energies thus resulting in an equilibrium distribution.

In Figure 1 we show the resulting electron spectra for source injection spectra with exponents, s = -2.2, -2.3 and -2.4. These calculated spectra, normalized at 1 GeV, are superimposed on four of the most comprehensive electron measurements above ~5 GeV where the solar modulation effects are small, (Golden et al., 1984, Tang , 1984, Muller, et al., 1997 and Nishimura, 1997), and also compared with a new IS electron spectrum below 5 GeV derived from the galactic radio spectrum in the polar direction (Peterson et al., 1999). The differences in the predicted spectra for various source spectral indices are quite large. Here we describe two ways to exploit these difference to determine both the source spectral index and the value of B_0 that best reproduce the data. The first uses the location of the peak energy, E_m, of the j x $E^{3.0}$ spectrum (Van der Walt and Webber, 1997). The calculated value of this energy for various values of the source spectral index and the interstellar B field is shown in Figure 2 along with limits from the measurements. Reasonable limits on the experimental value of E_m range from 6-15 GeV which in turn set limits on the combination of B and s as indicated in the Figure. In Figure 3 we show another way of comparing the data and predictions where we plot the ratio of the measured electron intensities at 10 and 1 GeV versus the ratio at 1000 and 10 GeV. Here the data is more restrictive eliminating values of s≤-2.2 for all reasonable B fields. The remaining limits from both Figures 2 and 3 give combinations of s=-2.3 to -2.4 and B_0=4-6 μG.

3. Summary and Conclusion

A comparison of calculations of the IS electron spectrum using a Monte Carlo diffusion program with experimental measurements above 1 GeV place limits on the electron source spectral index between -2.3 and -2.4 and on the typical IS magnetic field in the galactic plane within ±1 kpc of the Sun of 4-6 μG. These values should be compared with those determined from the low energy part of the electron spectrum obtained in a companion paper (Higbie et al., 1999).

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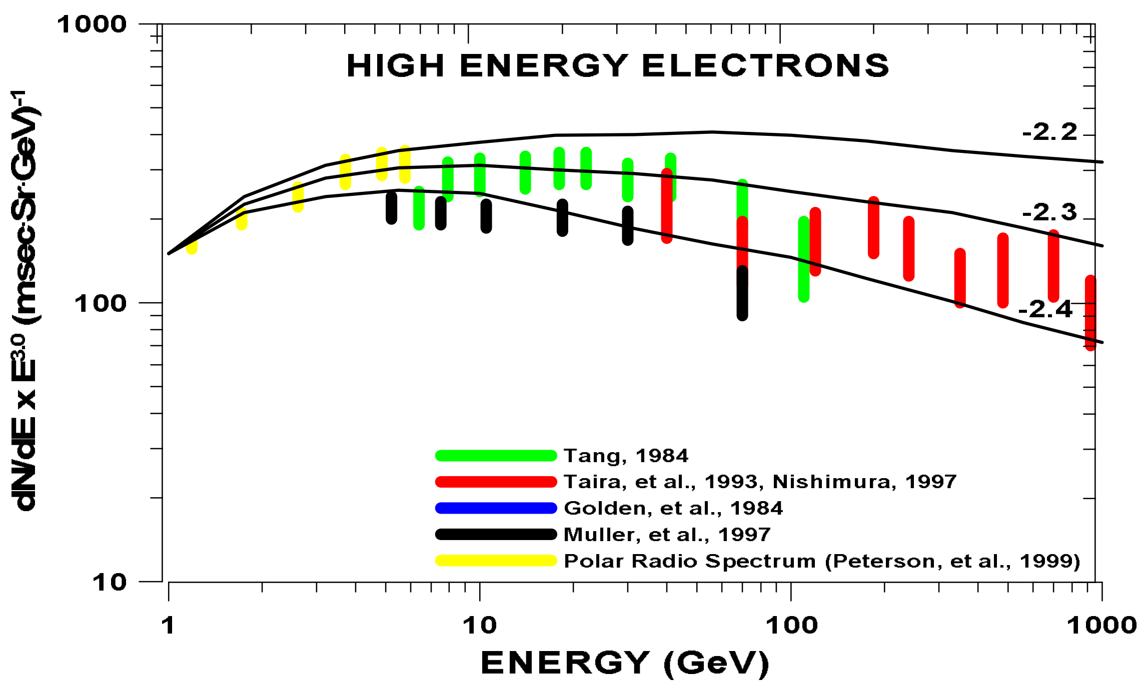

Figure 1: Direct measurements of primary electron spectrum above 6 GeV where solar modulation effects are minimized. Also shown is the local interstellar electron spectrum at lower energies derived from the galactic polar radio spectrum measurements (Peterson, et al., 1999).

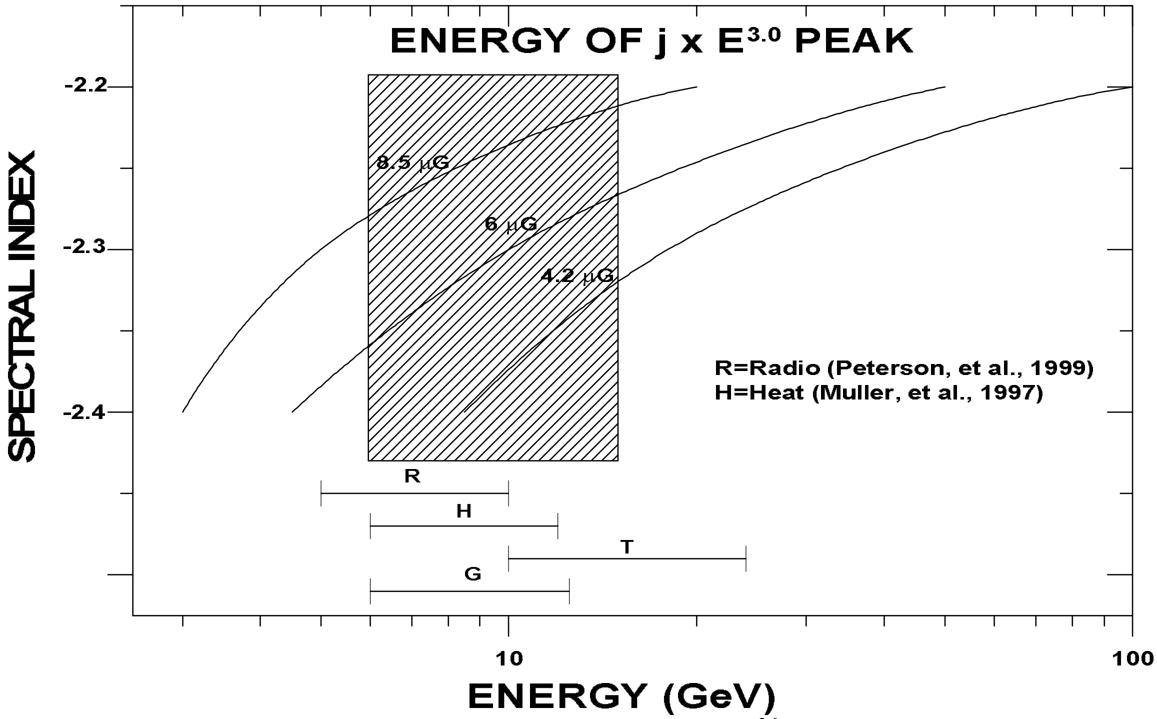

Figure 2: Comparison of the calculated location of the peak in the j x $E^{3.0}$ electron spectrum as a function of B and the electron source spectral index, and the measured location of the peak-shown overall as a shaded region and for individual measurements as energy bands labeled by 1st author of measurement.

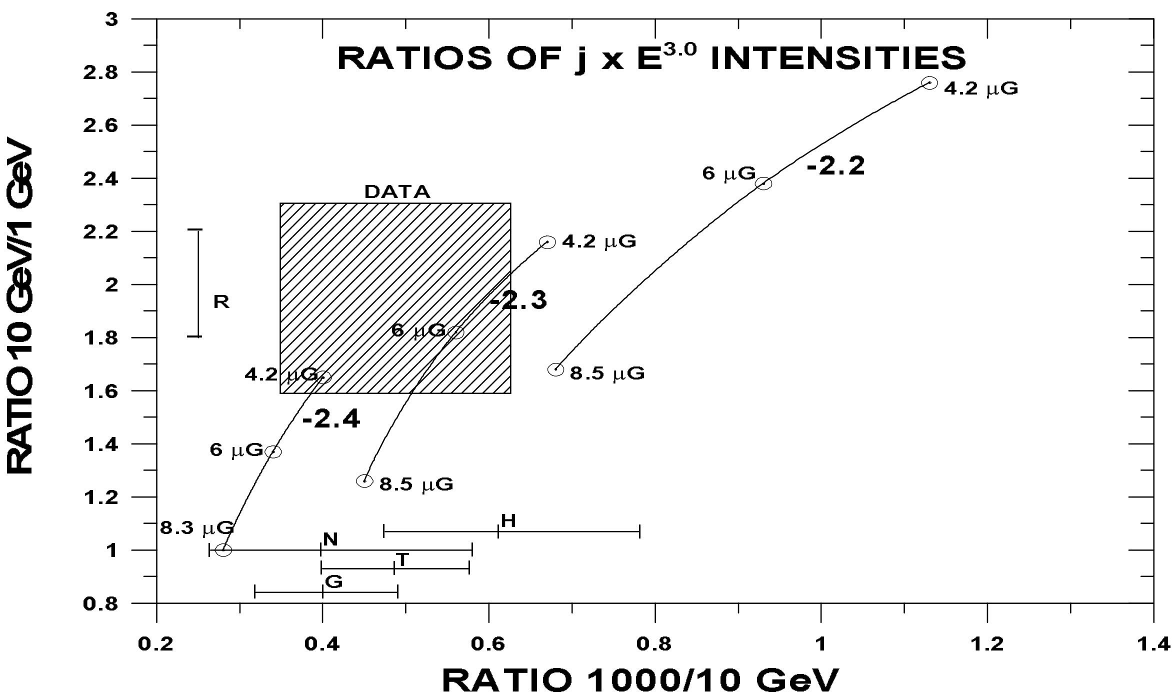

Figure 3: Measured and calculated ratios of 10:1 GeV and 1000:10 GeV interstellar electrons. The calculations are for different source spectra, -2.2, -2.3 and –2.4 and B fields ranging from 4.2-8.3 μG. The restrictions of parameter space by the electron spectrum measurements are indicated overall by the shaded area and individually by the banded labeling using the 1st author of the measurement.