OG 3.2.8

A Study of the Propagation of Cosmic Rays in the Galaxy Using a Monte Carlo Diffusion Model – The Source Spectra of Protons, Helium Nuclei and Electrons and the Locally Observed Spectra of These Components

W.R. Webber

Astronomy Department, New Mexico State University, Las Cruces, NM 88003, USA

Abstract

The shape of the spectra of cosmic ray protons and helium nuclei in the energy range from 1-100 GeV/nuc is very sensitive to the amount and distribution of the matter traversed. We derive spectra using a Monte Carlo diffusion calculation for typical local galactic matter densities, for source spectra $\sim P^{-2.25}/\beta$ and for a diffusion coefficient $(\text{escape length})^{-1} \sim P^{0.5}$, that accurately fits the B/C ratio at all energies. These calculated proton and helium spectra fit; (1) the measured spectra above >100 GeV/nuc, (2) some of the observed spectra between 1-100 GeV/nuc, when allowance is made for solar modulation, and (3) the spectra below 1 GeV/nuc that are needed to describe the low energy measurements again taking into account solar modulation. A similar Monte Carlo calculation is made for electrons. The source spectral index required to fit the electron observations from 1-1000 GeV is between -2.30 and -2.40.

1. Introduction

The source spectra of cosmic rays are modified by their propagation and escape from the Galaxy. If this escape can be parameterized by the form P^{-a} (or equivalently for the Monte Carlo diffusion calculation the diffusion coefficient $K \sim P^{a}$) and the source spectrum is of the form $dj/dp \sim P^{-s}$, then the spectrum after propagation at sufficiently high energies is of the form $dj/dp \sim P^{-(s+a)}$. In this calculation we use a Monte Carlo diffusion model and take the source spectrum $\sim P^{-2.25}/\beta$, and a diffusion coefficient $\sim P^{0.50}$ that accurately fits the B/C ratio at all energies (Webber, 1999). It is found that the propagated spectra are indeed $\sim P^{-2.75}$ at energies >100 GeV but begin to flatten noticeably at lower energies reaching a slope ~2.5 at ~20 GeV and a slope ~2.0 at 1 GeV/nuc. This flattening is also noticed in equivalent Leaky Box Model calculations. From the Monte Carlo calculations we find that this flattening depends on the matter integral, $n_0 dz$, in the z direction at the location of the Sun along with the diffusion properties including the location of the boundary (halo size). If one fixes the intensities of protons and helium nuclei at, say, 1 and 1000 GeV/nuc, based on low energy and high energy measurements, then the details of the spectra of both protons and helium nuclei are quite closely contained within the energy range 1-1000 GeV/nuc. After allowance is made for solar modulation effects only a few of the measurements in this energy range are found to fit the calculated spectra.

2. Calculation of the IS Proton and Helium Nuclei Spectra

In this calculation we use a one dimensional Monte Carlo diffusion model, cross checked by Leaky Box Model calculations. We assume that the injection spectra of both protons and helium nuclei are given by $dj/dP \sim P^{-2.25}/\beta$ where P is rigidity and the diffusion coefficient at z=0 is given by $K_0 = 2\text{x}10^{28}\, P^{0.50}$ cm^2 sec^{-1} above 1 GeV. Other details of the Monte Carlo calculation are described in Webber and Rockstroh, 1997. A most important parameter in this calculation is the line integral, $I_m = \int n\, dz$, of the matter density perpendicular to the disk, along with the distance to the boundary, z_B, in kpc (the size of the halo). The combination of parameters with $n_0 = 1.2$ cm^{-3}, $z_m = 0.2$ kpc, $z_B = 3$ kpc, fits the B/C ratio at both low (1 GeV/nuc) and high (100 GeV/nuc) energies (Webber, 1999).

The proton and helium spectra ($j \times E^{2.5}$) are required to have values between $(3.3 \pm 0.3) \times 10^3$ and (2.0 ± 0.2)

x 10^2 at 1 GeV/nuc and (3.8±0.6) x 10^3 and (2.0±0.5) x 10^2 at 1000 GeV/nuc respectively for proton and helium nuclei. These limits are set at the low energy end by the spectra needed in solar modulation studies to fit the low energy data and at high energies by the available measurements (Webber, 1997). Already these intensity limits restrict the overall source spectral induces of both components to be in the range of -2.25 to -2.30 if the diffusion coefficient is taken to be ~$P^{0.50}$.

In Figure 1 we show the calculated hydrogen spectrum (on a greatly expanded j x $E^{2.5}$ scale) and in Figure 2 the calculated helium spectrum, for source spectra ~$P^{-2.25}/\beta$ and for each case the calculated spectra are shown for a force field solar modulation of 400 MV and 800 MV. These spectral shapes are very closely constrained by the limits on the propagation parameters themselves.

For the existing data between 1-1000 GeV/nuc we show three examples. The data of Ryan et al., 1972, above 12 GeV/nuc which is only weakly affected by solar modulation; the data of Webber, Golden and Stephens, 1987, as representative of a solar modulation level of 400 MV and the I-Max data of Menn et al., 1999, representative of a solar modulation level of 800 MV. Space limitations do not allow us to discuss other data including several new measurements. However, all of this other data gives higher intensities below ~10 GeV/nuc (ok) and lower intensities above 10 GeV/nuc (not ok) than the I-Max data even though the solar modulation levels at the times of these measurements are <u>all</u> lower than I-Max, e.g., ϕ=400-600 MV. It is thus not possible to fit <u>any</u> of these other new measured spectra with propagated spectra, given the intensity limits chosen here at 1 and 1000 GeV/nuc and source exponents between -2.25 and -2.30. The data that is shown fits the calculated proton spectra better than the calculated helium spectra. Differences in these individual measurements in this intermediate energy range beyond those attributable to solar modulation effects apparently exist. In spite of these experimental differences, it is unlikely that the source spectra of either of these components can lie outside the broad range -2.25 to -2.35, given a diffusion coefficient ~$P^{0.50}$, based on both higher and lower energy data.

3. Summary and Conclusions

Using calculations from a Monte Carlo diffusion program the IS spectra of proton and helium nuclei are found to flatten significantly in the range of 1-100 GeV/nuc. This is caused by the local matter density and by the diffusion properties of cosmic rays in the Galaxy. This flattening, along with intensities measured both below 1 GeV/nuc and above 1000 GeV/nuc, lead to very specific predicted spectra for both components in the 1-1000 GeV/nuc range. Except for the examples noted here, the measured spectra of these two components in this intermediate energy range do not fit very well those calculated in this paper. Those examples which do look more or less like the expected calculated spectra after solar modulation serve to define a source spectra index in the range of -2.25 to -2.30 for both protons and helium nuclei. This is very similar to but perhaps slightly flatter than the source spectral required to fit cosmic ray electrons above ~1 GeV using the same propagation model (Rockstroh et al., 1999).

References

Menn, W., et al., 1999, Ap.J., submitted

Rockstroh, J.M. et al., 1999, paper OG 3.2-16, this conference

Ryan, M.J., et al., 1972, Phys. Rev. Lett., <u>28</u>, 985

Webber, W.R., Golden, R. And Stephens, S.A., 1987, Proc 20th ICRC <u>1</u>, 325

Webber, W.R. and Rockstroh, J.M., 1997, Adv. Space Rev., <u>19</u>, 817

Webber, W.R., 1997, Space Sci. Rev., <u>81</u>, 107

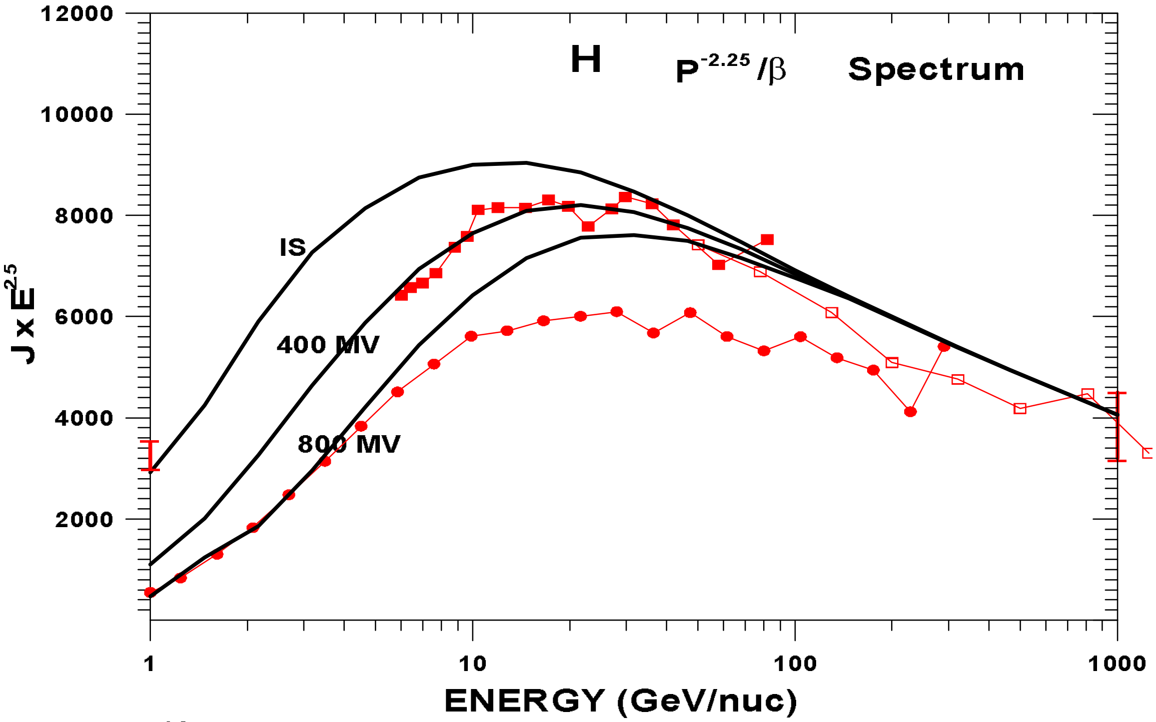

Figure 1: The j x $E^{2.5}$ spectrum of hydrogen calculated with a Monte Carlo galactic propagation program using a source spectrum ~$P^{-2.25}/\beta$. Solar modulation levels of 0, 400 and 800 MV are shown. The data are: open squares, Ryan, et al., 1972; solid squares, Webber, Golden and Stephens, 1987; solid circles, Menn, et al., 1999.

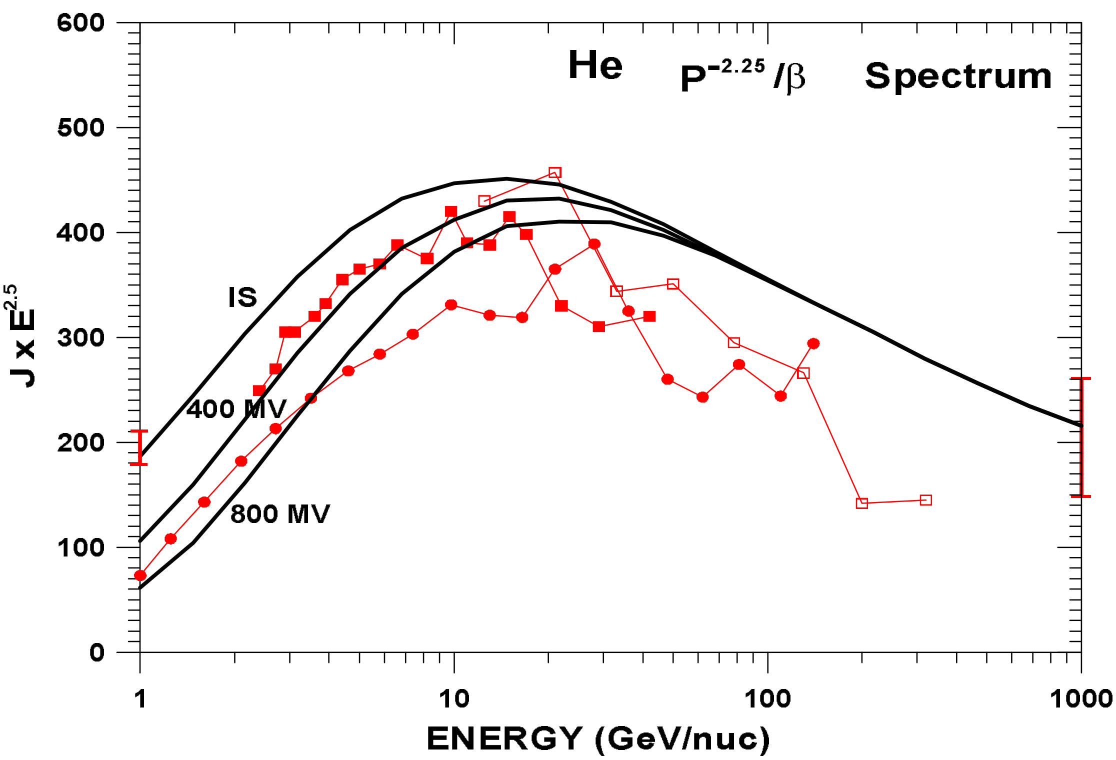

Figure 2: The j x $E^{2.5}$ spectrum of helium calculated using a Monte Carlo propagation program with a source spectrum ~$P^{-2.25}/\beta$. Solar modulation levels of 0, 400 and 800 MV are shown. Data symbols same as Figure 1.