Propagation models for CR nucleons and electrons and predictions of the Galactic gamma-ray spectrum

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ABSTRACT

We have further developed our numerical code for diffusive cosmic-ray propagation of nucleons and electrons with full spatial and energy dependence. This enables us to compute the spectrum over the Galaxy for quite general models based on realistic distributions of CR sources, matter and radiation fields. The model is first tuned to give consistency with secondary/primary nucleon data; it is then used to compute the electron spectrum and finally γ-ray intensities from bremsstrahlung and inverse Compton emission. The predictions are compared with recent data.

1. INTRODUCTION

The numerical solution of the cosmic-ray transport equation in the Galaxy was explored in our paper at the 23rd ICRC [1]. With the availability of abundant data from the Compton Gamma-Ray Observatory such calculations have become increasingly relevant; we have therefore continued to pursue this subject, and here we summarize the first complete set of results. Our rationale is that a great variety of observational data - composition and spectrum, gamma-rays, radio, etc. all give constraints of different kinds on Galactic cosmic-ray origin and propagation. The aim is to find at least one model which is consistent with all types of available data, and then to see what variations on this model are allowed; the present results are still just a first step in that direction. For example we might hope to be able to shed some light on the question of the extent of the propagation region, for which current estimates vary widely. Several different processes are involved including diffusion and spatially varying energy losses; our Galaxy model has properties derived from observational data on gas and radiation distributions and uses plausible cosmic-ray source distributions. An important feature of our approach is the inclusion of CR nucleons and electrons in the same model, which ensures consistent treatment of the two components.

2. MODEL AND NUMERICAL METHOD

The standard cosmic-ray transport equation for nucleons and electrons is written in the form:

$$\partial\psi(\vec{r},E,t)/\partial t = q(\vec{r},E) + \vec{\nabla}.[D\vec{\nabla}\psi \;-\vec{V}\;\psi] + \frac{\partial}{\partial E}[\psi\frac{dE}{dt}] - \sigma_i\rho v\psi - \frac{\psi}{\tau_r}.$$

We solve the cylindrically symmetric 3-D case with $\psi = \psi(R,z,E,t)$. First we solve completely for the primaries, and then run again for secondaries with the source term being replaced by the product of progenitor flux, gas density and cross section. The solution is generated on a grid in $(\vec{r},E)$; starting from the initial condition $\psi(\vec{r},E,0) = 0$ we integrate forwards in time until a steady-state is reached. Although we are interested only in the steady-state the time-evolution method has the advantage that the boundary conditions are straightforward to implement. We use a modified Crank-Nicolson scheme with upstream differencing and operator splitting to handle the spatial and energy propagation. The energy loss term includes the (spatially dependent) effects of ionization, bremsstrahlung, synchrotron and inverse-Compton losses. We impose the boundary condition $\psi(-z_h) = \psi(z_h) = 0$ for a 'halo' full thickness of $2z_h$. The diffusion coefficient is assumed to depend on rigidity $\Re$ as $D = D_o$ for $\Re < \Re_o$ and $D = D_o(\Re/\Re_o)^\delta$ for $\Re > \Re_o$ [2],[3]. Nucleons and electrons are assumed to have the same values of D_o, $\Re_o$, and δ. In [3] it was shown that the convection term is small and it is set to zero in this analysis.

The HI density as a function of (R,z) is taken from [6]; their distribution has $\int n_{HI}dz$=6.2 10^{20} cm^{-2}, FWHM = 0.23 kpc ; for molecular hydrogen we use the profile from [7] with $\int n_{H_2}dz = 5\ 10^{20}$ cm^{-2}, FWHM =0.14 kpc (inner Galaxy averages);

we take the extensive (T$\approx 10^4$K, $\rho \approx 0.025$ cm^{-3}) warm ionized medium from [8],[9] with N_H= 2 10^{20} cm^{-2}, FWHM = 3 kpc. The electron injection spectrum $q(E)$ is assumed to be a power-law with index -2.4 [4]. As normalization for the steady-state electron $\psi(R = R_o, z = 0, E)$ we use the interstellar value at 1 GeV (2 10^{-5} cm^{-2}sr^{-1} s^{-1} MeV^{-1}) derived from an analysis of COS-B γ-ray data [5]. The distribution of CR *sources* is assumed to follow that of SNR [16]. For inverse-Compton losses the radiation field is based on our calculation [10], including optical, far-infrared and 2.7K components; for synchrotron losses the magnetic field is taken as 6 e$^{-z/5kpc}\mu$G.

3. NUCLEONS

The first step was to adjust the model to agree with CR nucleon data. We adopted z_h= 3kpc [11] and adjusted the other parameters to reproduce B/C as a function of energy.

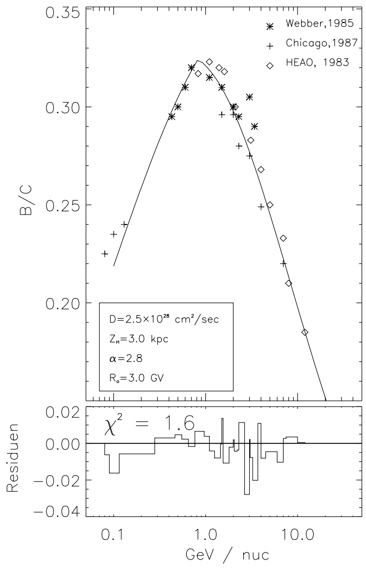


Fig 1 shows the agreement is satisfactory for the parameters D_o=2.5 10^{28} cm^2 s^{-1}, $\Re_o$ = 3 GV, δ=0.6. The predicted ^{10}Be/B is consistent with the measured value[11], so we adopt these parameters as our standard model. They are of course not unique, and study of the allowed ranges will be made in future work; this will be more important when the ^{10}Be spectrum is accurately measured. The parameters are consistent with values from analytical treatments [2],[3] but are tuned more precisely to our 3-D model.

Fig 1: *Energy dependence of B/C using our standard set of parameters*

The radial distribution of nucleons is compared with that deduced from COS-B γ-ray data [12] in Fig 2. Our model gives a more rapid radial variation than observed, indicating either the need for a much larger halo or an alternative model for the source distribution. A model with z_h=10 kpc improves the situation, and this is the subject of future work. The effect on γ-ray emission predictions which is the main aim of this paper, is however minor.

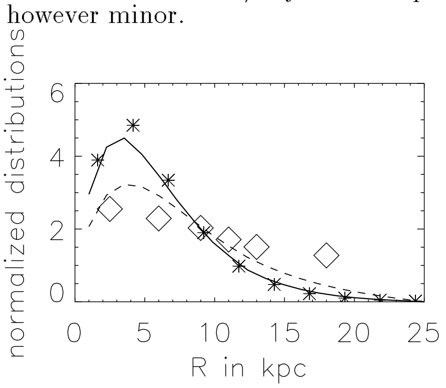


Fig 2: *Galactocentric variation of cosmic-ray density from our standard model (full line) and a model with z_h = 10 kpc (dotted line), compared with the gamma-ray emissivity gradient deduced from COS-B 70-5000 MeV data (Strong et al. 1988) (diamonds). The assumed source distributed is also shown (asterisks).*

4. ELECTRONS

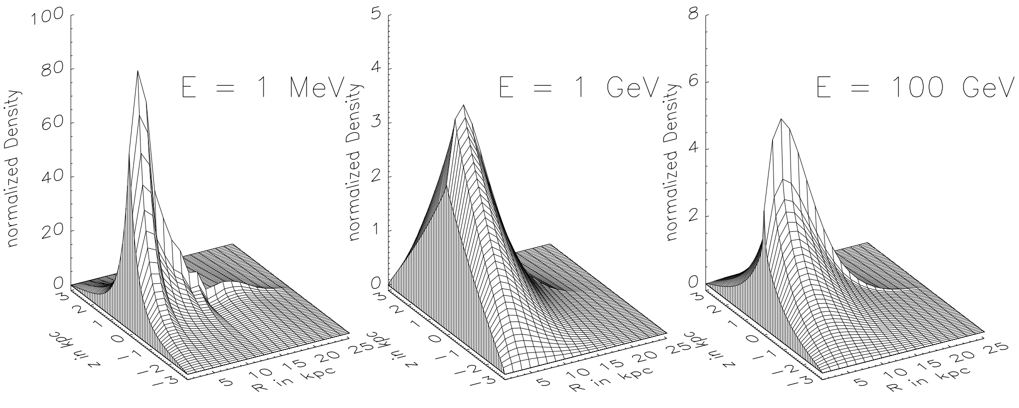


Fig 3: *Electron distribution as function of radius R and height z from the Galactic plane, for 1 MeV, 1 GeV and 100 GeV.*

Fig 3 shows the electron distribution in (R,z) for energies 1 MeV, 1 GeV and 100 GeV. At low energies the effect of energy losses forces the distribution in R to follow closely the sources; at higher energies the distribution is broader, and eventually the inverse-Compton and synchrotron losses curtail the distribution at large distances.

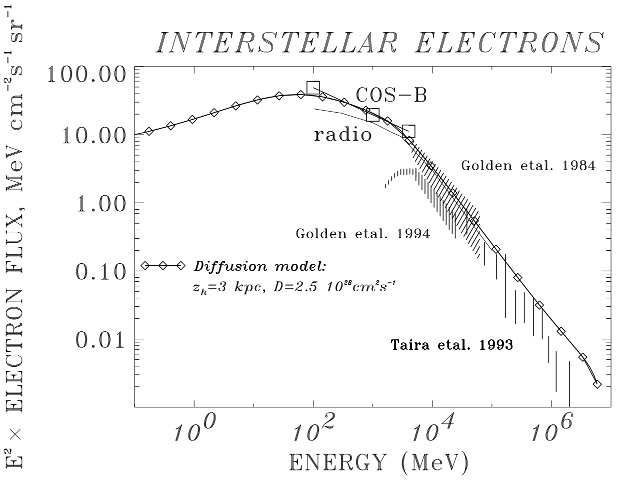
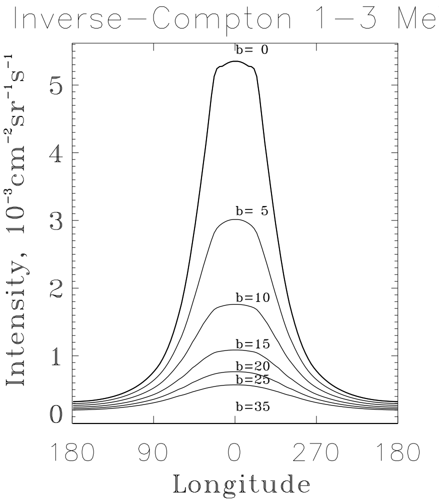


Fig 4: *Local electron spectrum based on the model (diamonds) compared to direct measurements [17], [18] and estimates based on gamma rays [5] and radio data [4].*

Fig 4 compares the local electron spectrum (R=8.5 kpc, z=0) with direct measurements and estimates based on radio and COS-B gamma-rays. The agreement is satisfactory up to 100 GeV, so that the model is able to reproduce both nucleon and high-energy electron data simultaneously, although at high energies the observations indicate a slightly steeper spectrum which would imply a larger halo as also suggested by the nucleon results in Section 3. The constraints on electrons with E< 100 MeV from γ-rays are also reasonably well satisfied (Fig 6).

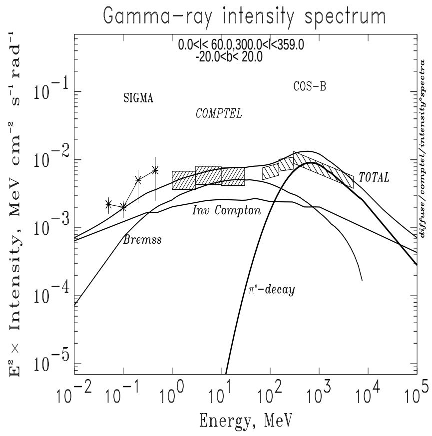
5. GAMMA RAYS FROM ELECTRON INTERACTIONS



The model has been used to compute the γ-ray intensity distribution from bremsstrahlung and inverse Compton interactions. The interstellar radiation field calculation for inverse-Compton is described in [10]. Fig 5 shows a sample result for one energy interval.

Fig 5: *Longitude distribution of predicted inverse-Compton gamma-ray intensity in the 1-3 MeV range, for various latitudes.*

For bremsstrahlung the observed gas column densities from HI and CO surveys were used. For comparison with observational data the spectrum of the intensity averaged over a given region of sky is required; we choose here 300^o<l<60^o, |b| <20^oas an illustration (Fig 6).



The sharp decrease in the bremsstrahlung due to ionization losses at low energies and the rather flat inverse-Compton spectrum causes the latter to dominate below 1 MeV; at high energies inverse-Compton again dominates since it is harder than the other components. Experimental points from COMPTEL [13],[15], SIGMA [14] and COS-B [12] are also shown; the general agreement indicates that the model is already good within a factor 2 over 5 decades of energy.

Fig 6: *Gamma-ray intensity spectrum of the Galaxy for 300^o<l <60^o, |b| <20^o. The bremsstrahlung, inverse-Compton, π^o-decay emission and the total (diamonds) are shown. SIGMA results refer to region around l=315^o*

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