SNR and fluctuations in the diffuse Galactic γ-ray continuum

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Abstract.
In studies of cosmic-ray propagation and diffuse continuum γ-ray emission from the Galaxy it has usually been assumed that the source function can be taken as smooth and time-independent, an approximation justified by the long residence time of cosmic-rays in the Galaxy. However, especially for electrons at high energies where energy losses are rapid, the effect of the stochastic nature of the sources becomes apparent and indeed has been invoked to explain the GeV excess in the diffuse emission observed by EGRET. In order to address this problem in detail a model with explicit time-dependence and a stochastic SNR population has been developed, which follows the propagation in three dimensions. The results indicate that although the inhomogeneities are large they are insufficient to easily explain the GeV excess. However the fluctuations should show up in the gamma-ray distribution at high energies and this should be observable with GLAST. We also show that estimates of the TeV continuum emission from the plane are consistent with the Whipple upper limit.

INTRODUCTION

The diffuse continuum γ-ray emission from the Galaxy measured by EGRET and COMPTEL has been the subject of many studies relating to cosmic-ray origin and propagation. Usually it has been assumed that the source function can be taken as smooth and time-independent, an approximation justified by the long residence time ($> 10^7$ years) of cosmic-rays in the Galaxy. We have previously described a numerical model for the Galaxy encompassing primary and secondary cosmic rays, γ-rays and synchrotron radiation in a common framework. Up to now our GALPROP code handled 2 spatial dimensions, (R,z), together with particle momentum p. This was used as the basis for studies of cosmic-ray (CR) reacceleration, the size of the halo, positrons, antiprotons, dark matter and the interpretation of diffuse continuum γ-rays. Some aspects cannot be addressed in such a cylindrically symmetric model: for example the stochastic nature of the cosmic-ray sources in space and time, which is important for high-energy electrons with short cooling times, and local inhomogeneities in the gas density which can affect radioactive secondary/primary ratios. The motivation for studying the high-energy electrons is the observation of the >1 GeV excess in the EGRET spectrum of the Galactic

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emission, which has been proposed to originate in inverse-Compton emission from a hard electron spectrum; this hypothesis can only be reconciled with the local directly-observed steep electron spectrum if there are large spatial variations which make our local region unrepresentative of the large-scale average spectrum. Strong et al. [1] presented a study of diffuse γ-rays based on the 2D model. First results from an extension of the model to 3D, which can cover these issues, are presented here.

MODEL

The GALPROP code, which solves the cosmic-ray propagation equations on a grid, has been entirely rewritten (in C++) using the experience gained from the original version and including both 2D and 3D spatial grid options. Cosmic-ray nuclear reaction networks are included with a comprehensive new cross-section database. This allows the models to be tuned on stable and radioactive CR primary/secondary ratios, in particular B/C and ^{10}Be/^{9}Be. The 2D mode essentially duplicates the original version. In 3D (x, y, z, p) the propagation is solved as before using a Crank-Nicolson scheme. The additional dimension increases the computer resources considerably but a 200 pc grid cell is still practicable. The main enhancement is the inclusion of stochastic SNR events as sources of cosmic rays. The SNR are characterized by the mean time t_{SNR} between events in a 1 kpc^3 unit volume, and the time t_{CR} during which an SNR actively produces CR. The propagation is first carried out for a smooth distribution of sources to obtain the long timescale solution; then the stochastic sources are started and propagation followed on a fine time scale for the last 10^7 years or so. For high-energy electrons (TeV) which lose energy on timescales of 10^5 years the effect is a very inhomogeneous distribution. The amplitude of the fluctuations depends on the two parameters t_{SNR} and t_{CR} which are both poorly known. t_{SNR} is adjusted to be consistent with the observed present number of SNR in the Galaxy and estimates of the SNR rate [2]; models for shock acceleration in SNR indicate $10^4 < t_{CR} < 10^5$ yr, the sources switching off at the adiabatic/radiative transition [3].

SNR AND EFFECT ON THE γ-RAY SKY

We consider a model with a hard electron injection spectrum (index 1.8) as used in Ref. [1] following the suggestion [4] that fluctuations could allow such a spectrum to be consistent both with the GeV γ-ray excess and the locally observed electron spectrum. For $t_{SNR} = 10^4$ years (corresponding to a “standard” Galactic SN rate 3/century) the TeV electron distribution is inhomogeneous, but still none of the spectra around $R = R_\odot$ resemble even remotely that observed locally (Fig. 1). For $t_{SNR} = 10^5$ years (Galactic SN rate 0.3/century) the distribution above 100 GeV is even more inhomogeneous and the spectrum fluctuates greatly (Fig. 2). Some of the spectra resemble that observed locally within a factor of a few, but still none is fully compatible with the local spectrum.

We conclude that the “hard electron spectrum” hypothesis for the EGRET γ-ray excess would require an SN rate much lower than standard, with correspondingly large power

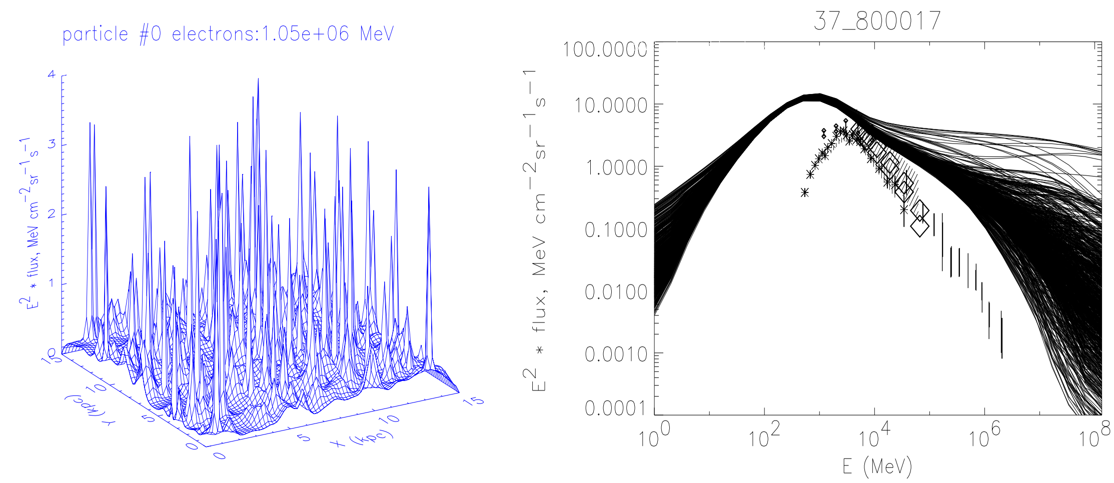

FIGURE 1. Distribution of 1 TeV electrons at $z = 0$ (left) and spectral variations in $4 < R < 12$ kpc (right) for $t_{SNR} = 10^4$ yr. Data points: locally measured electron spectra; references are given in Ref. [1], with additional data from Ref. [5].

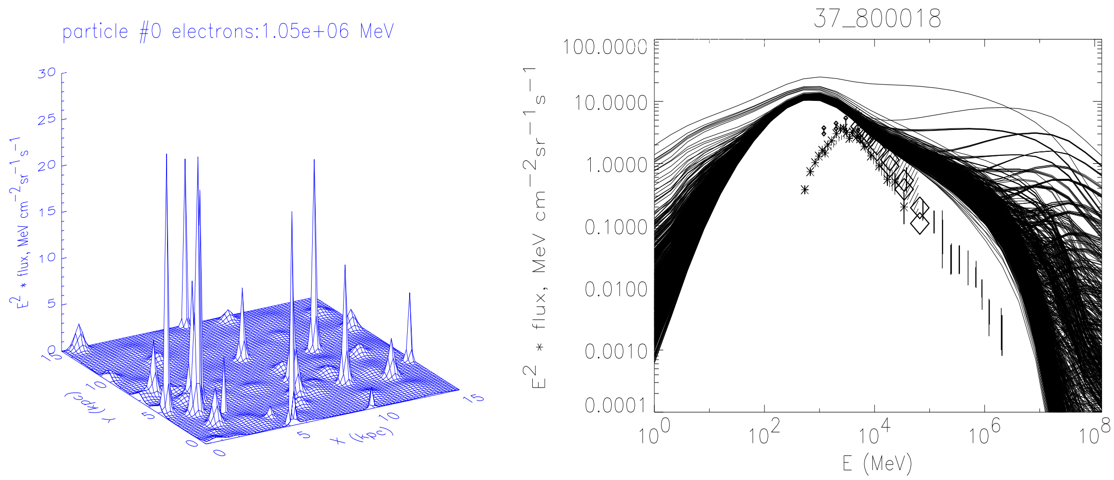

FIGURE 2. Distribution of 1 TeV electrons at $z = 0$ (left) and spectral variations in $4 < R < 12$ kpc (right) for $t_{SNR} = 10^5$ yr. Data as Fig. 1.

requirements for acceleration of electrons per SNR. It is possible that the rate of *CR-producing* SNR could be lower than that of all SNR, so that a sufficiently low rate could be possible, but this is unlikely in view of the power requirements. The CR luminosity in this model is 2×10^{41} erg s^{-1}; for 3 SNR/century we require 2×10^{50} erg/SNR in CR which is plausible (for 10^{51} erg and 20% acceleration efficiency: see Ref. [6] for discussion) but for 0.3 SNR/century we need 2×10^{51} erg/SNR in CR which would require quite another class of objects.

Our conclusion differs from that of Ref. [4], who found that a hard electron spectrum model is consistent with observations considering the fluctuations, but they included

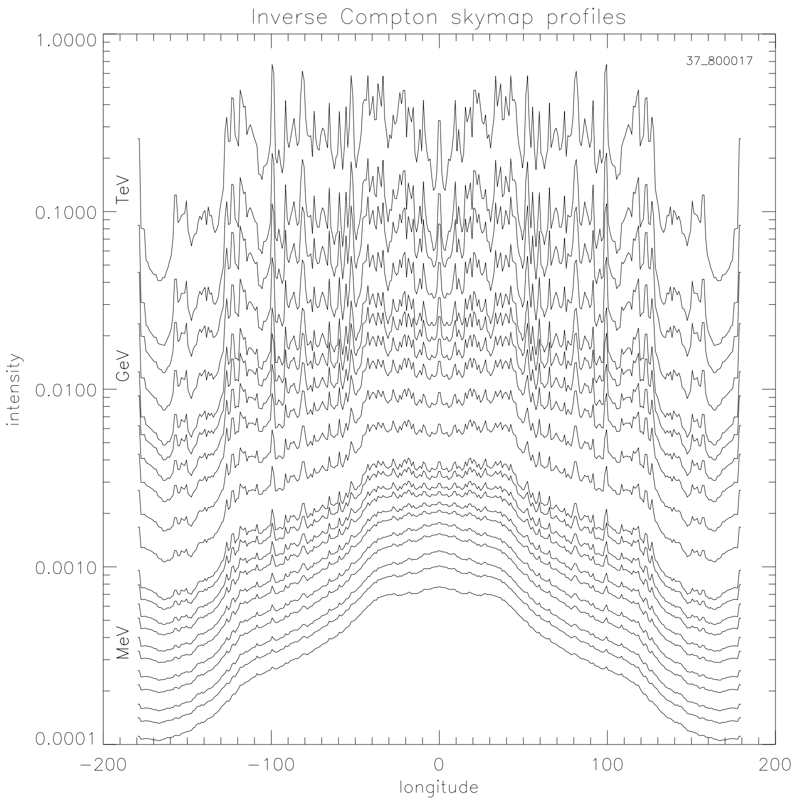

FIGURE 3. Inverse Compton γ-ray longitude distributions at $b = 0$ for γ-ray energies from 1 MeV (bottom) to 1 TeV (top). Note: the intensity scale is arbitrary and the curves have been shifted vertically for clarity.

however a dispersion in the electron injection spectral index which increases the variations further, although our tests of such a dispersion do not suggest that it eases the problem since a large number of SNR still contribute to the local electron spectrum at 1 TeV (see Fig. 1).

The inverse-Compton emission becomes increasingly clumpy at high energies due to the effect of SNR (Fig. 3). The effect is already visible at 1 GeV and will be an important signature at GLAST energies up to 100 GeV.

GALACTIC DIFFUSE TEV γ-RAYS

Recently observations of the Galactic plane (around $l = 40°$) have been reported by the Whipple Observatory [12], which place limits on the > 500 GeV intensity. We have extended our predicted spectrum for a hard electron injection spectrum to the TeV range (Fig. 4). Since the maximum energy of accelerated electrons is unknown we consider the extreme case of 100 TeV. Even for this case the predicted spectrum from inverse-Compton emission is compatible with the Whipple upper limit, and a lower cutoff energy will be also consistent with Whipple; it is clear that an improved limit would quickly

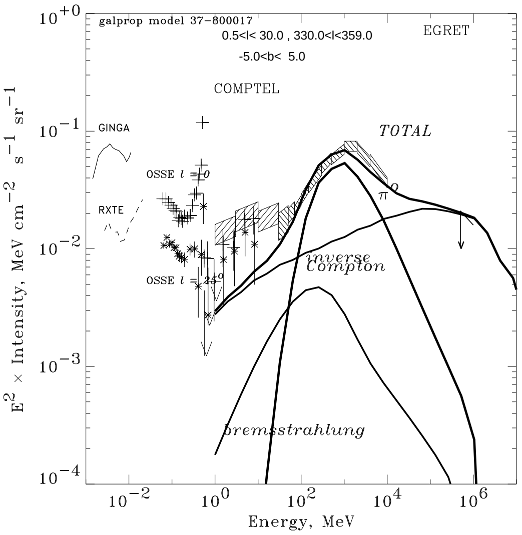

FIGURE 4. Spectrum of the inner Galaxy ($330° < l < 30°$, $|b| < 5°$ for model with $t_{SNR} = 10^4$ yr and hard electron injection spectrum (index 1.8) and cutoff at 100 TeV. Data: EGRET [7], COMPTEL [8], OSSE [9], GINGA [10], RXTE [11], Whipple [12]. Note that the Whipple upper limit is for $l = 40°$.

provide a critical test for models with hard electron injection spectra. The SNR shock-acceleration models [13] suggest a cutoff around 1 TeV which imply a cutoff in the γ-rays around 10 GeV in which case the predicted intensities are well below the Whipple limit and detection will be difficult.

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