Constraints on the Electron Injection Spectrum from Diffuse Gamma-Ray Observations

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Abstract

We perform a propagation calculation for cosmic ray electrons and positrons using a three-dimensional diffusion model, and use the resulting interstellar total electron spectrum to obtain the galactic diffuse photon spectrum due to inverse Compton, synchrotron and bremsstrahlung interactions consistently from radio to PeV energies. By considering the observed galactic non-thermal emission, we constrain the injection spectrum of electrons at acceleration. This contrasts with our earlier work (Porter & Protheroe 1997) which only utilised a simple one-dimensional model for the electron propagation, and did not consider constraints imposed by the observed non-thermal radio spectrum. We find that, if the electron injection spectrum is very flat, electrons with energies higher than $\sim 20$ TeV cannot be accelerated in sources located within the disk of the Galaxy. We discuss our results in terms of recent models for shock acceleration in shell-type supernova remnants.

1 Introduction:

Recently, X-ray observations (e.g. Koyama et al. 1995; Allen et al. 1997) of supernova remnants (SNRs) have been interpreted in terms of acceleration of electrons up to 100 TeV energies or higher (e.g. Reynolds 1996). Electrons accelerated to 100 TeV energies would eventually escape from their acceleration sites and rapidly cool through synchrotron radiation and inverse Compton (IC) scattering. Inverse Compton scattering of 100 TeV electrons on the cosmic microwave background radiation (CMBR), which is the principal target photon population at these energies, would produce a diffuse flux of gamma-rays at TeV energies. If this flux of diffuse gamma-rays is detectable, constraints can be placed on the average injection spectrum of primary electrons throughout the Galaxy. In turn, this provides a way of examining models for the acceleration of cosmic ray electrons in sources such as SNRs. In this paper, we consider possible injection spectra of primary cosmic ray electrons, and the resulting diffuse gamma-ray spectrum of the Galaxy.

2 Propagation Calculations:

We use a Monte Carlo code for propagating electrons and positrons in the Galaxy (Porter 1999), and we assume the Galaxy has a cylindrical geometry with a maximum radial dimension of $R_{\text{max}} = 20$ kpc. The propagation calculations are performed using a three-dimensional (3D) diffusion model, but the electron and positron distributions are obtained only for the 2D case ($R, z$) to take into account the 2D nature of the models for the matter distribution, radiation field and magnetic field we use.

We take a halo half-height of 4 kpc beyond which cosmic rays escape the Galaxy, and adopt a diffusion coefficient which is constant at $4.3 \times 10^{28}$ cm$^2$ s$^{-1}$ below a rigidity of $\rho = 4.7$ GV and increases as $(\rho/4.7$ GV)$^{0.5}$ above 4.7 GV. These values were obtained from a propagation model analysis (Porter 1999) of the abundances of $^{10}$Be and $^{26}$Al measured by the Voyager spacecraft (Lukasiak et al. 1994a,b). The distribution given by Strong & Moskalenko (1998) is used for the radial distribution of primary electron sources which are assumed to be uniformly distributed in the $z$ direction with half-height 0.2 kpc. The galactocentric radius of the Sun is taken to be 8.5 kpc. The injection spectrum of primary electrons is taken as a power-law $Q(E) \propto E^{-\gamma}$, and we consider values of $\gamma$ at injection in the range 1.8–2.4. Secondary electrons and positrons are assumed to be produced in inelastic collisions between cosmic ray nuclei and gas in the interstellar medium, and the source function for these particles is constructed as described by Porter (1999).
We use realistic models of the radiation fields (Porter 1999), matter distribution (Dickey and Lockman 1990; Bronfman et al. 1988; Cordes et al. 1991), and magnetic field (Beck et al. 1996). Electrons lose energy while propagating via ionisation, bremsstrahlung, synchrotron and inverse Compton (IC) processes; for IC losses we include Klein-Nishina effects at high energies.

Figure 1 shows a comparison of direct measurements of the electron intensity spectrum in the solar vicinity, spectra derived from non-thermal radio measurements and our calculated spectra (primary electrons + secondary electrons and positrons) using the Monte Carlo method for injection indices $\gamma = 1.8$ and $\gamma = 2.4$. The normalisation for the primary spectra are obtained by adjusting the predicted primary spectra so that the total spectra (primary + secondary) agree with the observations around 10 GeV (Nishimura et al. 1995 and references therein). At high energies both of the calculated spectra over-predict the data to some degree. However, following the discussion of Pohl & Esposito (1998) we do not require agreement between our predicted spectra and the locally observed spectrum above 30 GeV or so. See Porter (1999) for full details.

**Figure 1:** *Local interstellar electron spectra for injection spectral indices (i) $\gamma = 1.8$ and (ii) $\gamma = 2.0$. Solid line: total spectra; dashed line: primary electron spectra; dotted line: secondary electron and positron spectrum. Data: Nishimura et al. 1995 and references therein.*

### 3 Diffuse Photon Spectra:

Using our predicted electron and positron distributions, we calculate the diffuse photon emissivity due to synchrotron, bremsstrahlung and IC interactions, and perform line-of-sight integrations to obtain the intensity spectra of diffuse galactic radiation. We calculate the emissivity of $\pi^0$-decay photons using the same hadronic interaction model, cosmic ray and gas distributions as for the secondary electron/positron source distribution.

We use the observed galactic non-thermal emission to select possible source models, since this is a constraint that must be satisfied for any plausible model. Figure 2 compares our predicted non-thermal spectra with high latitude data (Lawson et al. 1987; Reich & Reich 1988; Broadbent et al. 1989). It can be seen soft injection spectra ($\gamma \sim 2.4$) provide a poor fit to the data at all frequencies. For harder injection spectra ($\gamma \sim 1.8 - 2.0$) significantly better agreement is obtained across the whole frequency range. Since soft injection spectra are not favoured by the data, we only consider $\gamma$ in the range 1.8–2.0 further.

Figures 3a and 3b compare our predicted high energy diffuse spectra in the direction of the inner Galaxy with satellite data and an air shower array upper limit in the same direction. At high energies, a cut-off in the injection spectrum would be expected (e.g. Protheroe & Stanev 1999), and we have introduced exponential cut-offs in the injection spectrum at 100 and 1000 TeV respectively. For a $\gamma = 1.8$ injection spectrum, electrons cannot be accelerated to energies higher than $\sim 20$ TeV or so without violating the Tibet upper limit. For a $\gamma = 2.0$ injection spectrum, electrons can be accelerated up to 1000 TeV without conflicting with the air shower upper limit.

Figures 4a and 4b compare our predicted high energy diffuse spectra in the direction of the outer Galaxy with COS-B data and air shower array upper limits. For a $\gamma = 1.8$ spectrum the constraint on the maximum attainable energy again is low, perhaps $\sim 10$ TeV at most. For a $\gamma = 2.0$ spectrum
Figure 2: Non-thermal intensity in the direction of the galactic pole. Solid line: $\gamma = 1.8$ injection spectrum; dashed line: $\gamma = 2.0$ injection spectrum; dotted line: $\gamma = 2.4$ injection spectrum. Data points: Lawson et al. 1987 (38 MHz); Brodnent et al. 1989 (408 MHz); Reich & Reich (1988) (1420 MHz).

The CASA-MIA upper limit constrains the maximum energy to $\sim 100$ TeV or lower.

Figure 3: Diffuse gamma-ray spectrum toward the inner Galaxy ($-60^\circ \leq l \leq 60^\circ, |b| \leq 10^\circ$) for (a) $\gamma = 1.8$, and (b) $\gamma = 2.0$. Theoretical predictions: dashed line (IC); dotted line ($\pi^0$-decay); dash-dotted line (bremsstrahlung); solid lines (total). Lower dashed curve calculated for exponential cut-off at 100 TeV; higher dashed curve for cut-off at 1000 TeV. Data: solid circles, EGRET data (Hunter et al. 1997); solid boxes and open stars, COS-B data (Paul et al. 1978); upper limit $T$, Tibet air shower array (Amenomori et al. 1997).

4 Discussion and Conclusions:

If it is accepted that the high energy diffuse gamma-ray spectrum is due to IC gamma-rays from electrons accelerated with hard injection spectra (e.g., Pohl & Esposito 1998), a natural corollary is the resulting gamma-ray spectrum must exhibit a cut-off, related to the cut-off in the injection spectrum, to ensure agreement with the various upper limits provided by air shower arrays. For a $\gamma = 1.8$ average injection spectrum, we have shown that the high energy cut-off must be $\sim 10$ TeV in the galactic plane. For a $\gamma = 2.0$ average spectrum, the maximum attainable energy is higher: $\sim 1000$ TeV toward the inner Galaxy and $\sim 100$ TeV toward the outer Galaxy.

Recently, Baring et al. (1998) presented models for shock acceleration in SNRs which produce very flat electron spectra similar to the $\gamma \sim 1.8-2.0$ spectra found in the present work. If the average injection spectrum of electrons from such objects is indeed $\gamma \sim 1.8$, our calculations support the view of Baring et al. (1998) that shell-type SNRs located within the galactic plane cannot be sources of galactic cosmic rays with energies up to 1000 TeV; in their model cosmic rays with energies $\sim 100$ TeV and higher must be accelerated in low gas density regions, such as at high galactic latitudes. On
Figure 4: Diffuse gamma-ray spectrum toward the outer Galaxy ($50^\circ \leq l \leq 220^\circ$, $|b| \leq 10^\circ$) for (a) $\gamma = 1.8$, and (b) $\gamma = 2.0$. Theoretical predictions: as in the key of Figure 3. Data: solid boxes and open stars, COS-B data (Paul et al. 1978); upper limit $T$, Tibet air shower array (Amenomori et al. 1997); upper limit U-M, Utah-Michigan array (Matthews et al. 1991); upper limit C-M, CASA-MIA (Borione et al. 1998).

The other hand, if the average injection spectrum is $\gamma \sim 2.0$, acceleration by sources located within the disk of the Galaxy is possible up to 100 TeV, and even higher in the inner Galaxy.

References
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