Deciphering diffuse Galactic continuum gamma rays

I.V. Moskalenko\textsuperscript{1,2} and A.W. Strong\textsuperscript{1}

\textsuperscript{1}Max-Planck-Institut f"ur extraterrestrische Physik, D-85740 Garching, Germany
\textsuperscript{2}Institute for Nuclear Physics, Moscow State University, 119 899 Moscow, Russia

Abstract

Inverse Compton scattering appears to play a more important role in the diffuse Galactic continuum emission than previously thought, from MeV to GeV energies. We compare models having a large inverse Compton component with EGRET data, and find good agreement in the longitude and latitude distributions at low and high energies. We test an alternative explanation for the $\geq 1$ GeV $\gamma$-ray excess, the hard nucleon spectrum, using secondary antiprotons and positrons.

Introduction.

We are developing a model which aims to reproduce self-consistently observational data of many kinds related to cosmic-ray origin and propagation: direct measurements of nuclei, electrons and positrons, gamma rays, and synchrotron radiation (Strong 1998). Here we concentrate on the inverse Compton (IC) contribution to the diffuse Galactic continuum gamma-ray emission. Recent results from both COMPTEL and EGRET indicate that IC scattering is a more important contributor to the diffuse emission that previously believed. COMPTEL results (Strong 1997) for the 1–30 MeV range show a latitude distribution in the inner Galaxy which is broader than that of HI and H\textsubscript{2}, so that bremsstrahlung of electrons on the gas does not appear adequate and a more extended component such as IC is required. The broad distribution is the result of the large $z$-extent of the interstellar radiation field which can interact cosmic-ray electrons up to several kpc from the plane. At much higher energies, the puzzling excess in the EGRET data above 1 GeV relative to that expected for $\pi^0$-decay has been suggested to originate in IC scattering (e.g., Pohl 1998) from a hard interstellar electron spectrum. We test this scenario with comparisons of the predicted gamma-ray sky with EGRET data. We also test an alternate hypothesis, the hard nucleons spectrum, using antiprotons and positrons.

Models.

We consider a propagation model with reacceleration using parameters derived from isotopic composition (Strong 1998). Energy losses for electrons by ionization, Coulomb scattering, bremsstrahlung, IC and synchrotron are included. A new calculation of the interstellar radiation field (ISRF) has been made based on stellar population models and IRAS and COBE data. An investigation of the effect of the anisotropy of the ISRF has shown that this has a significant influence on the intensity and distribution of the IC radiation. Photons moving away from the observer are scattered anisotropically, enhancing the radiation for example at high latitude. This effect is included in our models. The $\pi^0$-decay gamma rays are calculated explicitly from the propagated proton and Helium spectra (Dermer 1986, Moskalenko 1998a). The electron injection spectral index is taken

\footnote{1For more details see http://www.gamma.mpe–garching.mpg.de/~aws/aws.html}
Fig. 1. Left: Electron spectrum at $R_\odot = 8.5$ kpc in the plane, for models with and without reacceleration. Data points: direct measurements, see references in Moskalenko (1998a). Right: Synchrotron spectrum towards NGP for these electron spectra, compared to observational data.

as $-1.8$ in the case of reacceleration models; this value is necessary to obtain consistency with radio synchrotron spectrum towards the Galactic pole. Without reacceleration an injection index near $-2.0$ is required. Figure 1 shows the electron spectrum at $R_\odot = 8.5$ kpc in the disk for these models, and the synchrotron spectrum towards the Galactic pole. Following Pohl (1998), for the present study we do not require consistency with the locally measured electron spectrum above 10 GeV since the rapid energy losses mean that this is not necessarily representative of even the local interstellar average. (Agreement with the locally measured electron spectrum would require a break in the injection spectrum at a few GeV, as has often been adopted in the past). A halo size (distance from plane to boundary) of $z_h = 4$ kpc is adopted, consistent with the $^{10}Be$ analysis in the accompanying paper (Strong 1998).

**Comparison with EGRET data.**

Figure 2 shows the model latitude and longitude $\gamma$-ray distributions for the inner Galaxy for 70–100 MeV, convolved with the EGRET point-spread function, compared to EGRET Phase 1–4 data. The separate components are also shown. In this model the contributions from IC, bremsstrahlung and $\pi^0$-decay are about equal at 100 MeV. (Note that point sources such as the Vela pulsar have not been removed from the data, but we are here only interested in the large-scale profiles). The comparison shows that a model with large IC component can indeed reproduce the data. This energy range is close to that in which COMPTEL data led to similar conclusions (Strong 1997). Turning to high energies, Figure 3 shows profiles for 4000–10000 MeV; again the comparison shows that the adoption of a hard electron injection spectrum is a viable explanation for the $>1$ GeV excess. The latitude distribution here is not as wide as at low energies owing to the rapid energy losses of the electrons, so that an observational distinction between a gas-related $\pi^0$-component from a hard nucleon spectrum and the present IC model does not seem possible.

**Test for a hard nucleon spectrum using antiprotons and positrons.**

Another possible origin for the $>1$ GeV excess could be an interstellar nucleon spectrum which is harder than observed locally (e.g., Hunter 1997, Gralewicz 1997, Mori 1997).
Fig. 2. Left: Latitude distribution for 70–100 MeV as measured by EGRET, compared to reacceleration model with hard electron spectrum. Right: Longitude distribution for $|b| < 5^\circ$.

Fig. 3. Left: Latitude distribution for 4000–10000 MeV as measured by EGRET, compared to reacceleration model with hard electron spectrum. Right: Longitude distribution for $|b| < 5^\circ$.

Fig. 4. Left: Gamma-ray spectrum of inner Galaxy as measured by EGRET (Strong 1996b) compared to model with a hard nucleon spectrum. Right: $\vec{p}/p$ ratio for the ‘normal’ spectrum (solid lines) and for the hard nucleon spectrum (dashes) used for the $\gamma$-ray calculation shown on the left. The thick lines show the case with reacceleration. Dotted lines: calculations of Simon (1998). Data from: ■ Boezio (1997), ○ Bogomolov (1987,1990), △ Hof (1996), □ Mitchell (1996), ◊ Moiseev (1997).
Figure 4 (left) illustrates such a possibility; here we have used a nucleon injection spectrum which is a power law in momentum with index $-1.7$ (no reacceleration) giving after propagation a $\gamma$-ray spectrum which agrees reasonably with the EGRET data.

The $\bar{p}/p$ ratio expected for this case and the standard model compared to recent data is shown in Figure 4 (right). Our standard model calculation agrees with that of Simon (1998). For the case of a hard nucleon spectrum the ratio is still consistent with the data at low energies but becomes $\sim 4$ times higher at 10 GeV. Up to 3 GeV it does not conflict with the data with their large error bars. It is however larger than the point at 3.7–19 GeV (Hof 1996) by about $5\sigma$. On the basis of the $\bar{p}/p$ data point above 3 GeV we seem already to be able to exclude the hard nucleon spectrum, but confirmation of this conclusion must await more accurate data at high energies.

Figure 5 shows the interstellar positron spectrum, again for the standard and hard nucleon spectra. The formalism used is given in Moskalenko (1998a). The flux for the standard case agrees with recent data (Barwick 1998). For the hard nucleon spectrum the flux is higher than observed by factor $\sim 4$; this provides more evidence against a hard nucleon spectrum. However this test is less direct than $\bar{p}$ due to the difference in particle type and the large effect of energy losses.

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