The Diffusive Galactic GeV/TeV Gamma-Ray Background: Sources vs. Transport

Heinrich J. Völk

Abstract. The diffuse Galactic $\gamma$-ray background, as observed with EGRET on CGRO, exceeds the model predictions significantly above 1 GeV. This is particularly true for the inner Galaxy. We shall discuss here the contribution of the Galactic Cosmic Ray (GCR) sources, considered as unresolved, and in addition the possibility that the transport of the GCRs out of the Galaxy is not uniform over the Galactic disk. In both cases the spectrum of the diffuse gamma rays is harder than the GCR spectrum in the neighborhood of the Solar system, as observed in situ. The source contribution is a necessary and, as it turns out, significant part of the diffuse background, whereas the transport effect is one of several conceivable additional causes for the hard diffuse $\gamma$-ray spectrum observed.

INTRODUCTION

The observations of the diffuse Galactic $\gamma$-ray emission can be described rather well by a suitable model for the diffuse interstellar gas, GCR, and photon distributions (e.g. Hunter et al. 1997a). However, above 1 GeV the observed average diffuse $\gamma$-ray intensity, foremost in the inner Galaxy, $300^\circ < l < 60^\circ$, $|b| < 10^\circ$, exceeds the model prediction significantly. As far as the energetic particles are concerned, there are at least two possible explanations for this discrepancy (e.g. Weekes et al. 1997; Hunter et al. 1997b, and references therein). The high-energy $\gamma$-ray excess may indicate that the GCR spectrum observed in the local neighborhood is not representative of the diffuse CR population in the Galactic disk. An unresolved distribution of CR sources is the other possibility. Since the $\gamma$-ray emission is the product of the energetic particle intensity on the one hand, and of the gas density or the photon density, on the other, it is of course possible that deviations from the above model assumptions for these latter densities across the Galaxy can also lead to changes in the observed energy spectrum of the diffuse gamma rays. We shall not discuss such deviations here. We shall rather evaluate the contribution of the sources, assumed to be the ensemble of Supernova Remnant (SNR) shells,
following a recent calculation by Berezhko & Völk (1999). We shall also consider
the transport of the particles from the same sources out of the Galaxy to naturally
increase with decreasing Galactic radius (Breitschwerdt et al., 1991). We shall leave
aside the possibility of new sources of particles, not known in the neighborhood of
the Solar system.

GAMMA RAYS FROM THE ENSEMBLE OF SNRS

Since at best a handful of shell SNRs could be argued to have been detected up to
now in gamma rays, we shall ignore their discrete contributions and consider the CR
sources to be spatially averaged over the volume \( V_g = 2.5 \times 10^{60} \text{ cm}^3 \) of the Galactic
gas disk, with a radius of 10 kpc and a thickness of 240 pc. The corresponding gas
mass is \( M_g = 4 \times 10^9 M_\odot \) (Dickey & Lockman, 1990). The source input rate in the
form of energetic particle energy equals \( \nu_{SN} \delta E_{SN} \), where we take \( \nu_{SN} = 1/30 \text{ yr} \),
\( E_{SN} = 10^{51} \) erg. The efficiency per SNR is \( \delta < 1 \). The total number of localized
SNRs which still contain their shock accelerated CRs, called here the source CRs
(SCRs), is given by \( N_{SN} = \nu_{SN} T_{SN} \), where \( T_{SN} \) is their assumed life time, i.e. the
time until which they can confine the accelerated particles in their interior. Thus
\( N_{SN} \) is dominated by the population of old SNRs. We estimate \( T_{SN} \simeq 10^5 \text{ yr} \). After the time \( T_{SN} \) the SCRs rather quickly become part of the ordinary GCRs
that presumably occupy a large Galactic residence volume uniformly.

Acceleration model

We assume the overall SCR number inside a single SNR to be given by a power
law spectrum \( N_{SCR} dE \propto \epsilon^{-\gamma_{SCR}} dE \) in energy \( \epsilon \) in the relativistic range.
Averaged over the disk volume, the spatial density \( n_{SCR} \) of SCRs is given
\( n_{SCR} = N_{SCR} / V_g \), with energy density \( \epsilon_{SCR} = N_{SN} \delta E_{SN} / V_g \). In terms
of \( \epsilon_{SCR} \), we have

\[
n_{SCR}(\epsilon) = \frac{n_{0}^{SCR}(\gamma_{SCR} - 1)}{mc^2} \left( \frac{\epsilon}{mc^2} \right)^{-\gamma_{SCR}}
\]

(1)

and

\[
n_{0}^{SCR} = \frac{(\gamma_{SCR} - 2)\epsilon_{SCR}}{(\gamma_{SCR} - 1)mc^2},
\]

(2)

for \( \gamma_{SCR} > 2 \). The same expressions hold for the GCRs, given \( \epsilon_{GCR} \) and \( \gamma_{GCR} \).

For the SCR we may quite possibly have \( \gamma_{SCR} = 2 \), and then

\[
n_{0}^{SCR} = \frac{\epsilon_{SCR}}{mc^2 \ln(\epsilon_{max}/mc^2)};
\]

(3)

where \( \epsilon_{max} \simeq 10^5 mc^2 \) is the maximum SCR energy.
The $\pi^0$-decay production rate is given by

\[ Q_\gamma(\epsilon) = Z_\gamma \sigma_{ppc} N_g n(\epsilon), \quad (4) \]

(Drury et al. 1994), which leads to the ratio $R = Q^{SCR}_\gamma/Q^{GCR}_\gamma$ of the $\gamma$-ray production rates due to SCRs and GCRs, given by

\[ R(\epsilon_\gamma) = \frac{Z^{SCR}_\gamma N_{SN} \delta E_{SN}}{Z^{GCR}_\gamma (\gamma_{GCR} - 2) \ln(\epsilon_{max}/mc^2)V_g \epsilon_{GCR}} \times \zeta \left( \frac{\epsilon_\gamma}{mc^2} \right)^{\gamma_{GCR} - 2}, \quad (5) \]

where $\zeta$ is the ratio $N^{SCR}_g/N^{GCR}_g$, $N^{SCR}_g$ is the mean source gas density, and $N^{GCR}_g$ denotes the average gas density in the disk.

With $\delta = 0.2$, $\epsilon_{GCR} \approx 2 \times 10^{-12}$ erg/cm$^3$ for the relativistic part of the GCRs, and $\gamma_{GCR} = 2.75$ which results in $Z^{SCR}_\gamma/Z^{GCR}_\gamma = 10$ (Drury et al. 1994), we obtain

\[ R(\epsilon_\gamma) = 0.16 \zeta \left( \frac{T_{SN}}{10^5 \text{yr}} \right) \left( \frac{\epsilon_\gamma}{1 \text{ GeV}} \right)^{0.75}, \quad (6) \]

for $\gamma_{SCR} = 2$.

The total $\gamma$-ray spectrum measured from an arbitrary Galactic disk volume is then expected to be

\[ \frac{dN_\gamma}{d\epsilon_\gamma} = \frac{dN^{\gamma}_{GCR}}{d\epsilon_\gamma} [1.4 + R(\epsilon_\gamma)], \quad (7) \]

where the additional factor 0.4 is introduced to approximately take into account the contribution of GCR electron component to the diffuse $\gamma$-ray emission at GeV energies, and where $\frac{dN^{\gamma}_{GCR}}{d\epsilon_\gamma}$ is taken from the paper by (e.g. Hunter et al. 1997b).

"Leaky Box"-type model

We can derive very similar results from a leaky box-type balance equation

\[ \frac{n_{GCR}(\epsilon)}{\tau_c} = \frac{N_{SCR}(\epsilon)}{V_c(\epsilon)} \nu_{SN}, \quad (8) \]

where $V_c(\epsilon)$ is the energy-dependent residence volume occupied by GCRs that reach the gas disk during their constant mean residence time $\tau_c \approx 3 \times 10^7$ yrs in $V_c(\epsilon)$. In the case of an extended Galactic Halo, $V_c(\epsilon \gg 1 \text{GeV}) \gg V_g$ (Ptuskin et al. 1997). Using eq. (4) we can write

\[ \frac{n_{SCR}}{n_{GCR}} = \frac{V_c T_{SN}}{V_g \tau_c} = \frac{T_{SN}}{\tau_g}. \quad (9) \]
The GCR residence time in the disk volume

\[ \tau_g = \tau_c V_g / V_c = \frac{x V_g}{v M_g} \]  

(10)

can be derived from the measured grammage \( x = 14 v/c (\epsilon/4.4 \text{ GeV})^{-0.60} \text{ g/cm}^2 \), for \( \epsilon > 4.4 \text{ GeV} \), and \( x = 14 v/c \text{ g/cm}^2 \), for \( \epsilon < 4.4 \text{ GeV} \) (Engelman et al. 1990).

At relativistic energies \( \epsilon > m c^2 \), the GCR spectrum and the overall SCR spectrum \( N_{SCR} \propto \epsilon^{-\gamma_{SCR}} \) are connected by the relation

\[ \gamma_{SCR} = \gamma_{GCR} - 0.6 = 2.15. \]  

(11)

Taking \( \gamma_{SCR} = 2.15 \), which leads to \( Z_{\gamma}^{SCR} / Z_{\gamma}^{GCR} = 7.5 \) (Drury et al. 1994), we obtain for \( \epsilon_{\gamma} \geq 4.4 \text{ GeV} \):

\[ R(\epsilon_{\gamma}) = 0.06 \zeta \left( \frac{T_{SN}}{10^5 \text{ yr}} \right) \left( \frac{\epsilon_{\gamma}}{1 \text{ GeV}} \right)^{0.6} \]  

(12)

(Berezhko & Völk, 1999).

The question is, of course, whether the SN confinement time \( T_{SN} \) is time dependent. Probably this dependence is \( T_{SN}(\epsilon) = t_0 (\epsilon/\epsilon_{max})^{-5} \), where \( t_0 \) is the sweep-up time when the SNR enters the Sedov phase and the shock speed begins to decrease with time. For average ISM parameters \( t_0 \sim 10^3 \text{ yr} \).

RESULTS INCLUDING THE SCRS

In Fig. 1 we show the measurements by Hunter et al. (1997a) and our two estimates for the total \( \gamma \)-ray emission, from GCRs plus SCRs. They demonstrate that the SCR contribution for the acceleration model exceeds the leaky box values for all energies. The reason is that for our empirical model the acceleration efficiency for the relativistic part of the spectrum is only \( \delta \simeq 0.08 \). This is probably due to the fact that the mean injection efficiency at the SNR shock is lower than the values typically assumed for a parallel shock by a factor of a few. We take the lower value for the \( \gamma \)-ray emission in Fig.1 as the most reliable estimate for the expected diffuse \( \gamma \)-ray emission, including the SCRs. Nevertheless the SCR distribution, which is about 10 percent at GeV energies, becomes dominant beyond 100 GeV, and exceeds the GCR emission at 1 TeV by almost a factor of 10. It would be very interesting to detect the diffuse Galactic \( \gamma \)-ray emission at 1 TeV in order to test this prediction.

Until now we have only discussed the \( \gamma \)-ray emission from hadronic SCRs. In fact, there are many reasons to assume that electrons are equally well accelerated in SNRs, even if their injection into the shock acceleration process is much less well understood. The inverse Compton emission by SCR electrons can be comparable with the hadronic emission, even though it does not contribute at TeV energies. For a more detailed discussion we refer to the paper of Berezhko & Völk (1999).
FIGURE 1. The differential diffuse $\gamma$-ray energy flux vs $\gamma$-ray energy above 4.4 GeV (cf. Berezhko & Völk, 1999). The heavy symbols are the EGRET measurements, and the dash-dot line is the model prediction of Hunter et al. (1997a). The full curve corresponds to our acceleration model with $\gamma_{SCR} = 2$, whereas the dashed curve corresponds to the Leaky Box model. Both theoretical curves incorporate energy-dependent loss from the acceleration region.

TRANSPORT EFFECTS

The models used to fit the $\gamma$-ray data from, say, EGRET assume a GCR energy spectrum that is uniform throughout the Galaxy. This tacitly assumes that the GCR transport properties leading to the escape from the Galaxy are everywhere the same. However that needs not be the case, and in fact is almost certainly not true. The dynamical processes leading to GCR escape depend on the strength of the regular magnetic field and on its fluctuation characteristics, as well as on the CR pressure, and the gravitational field. An example is the formation of Parker bubbles which remove the enclosed CRs through their boyant rise into the Halo and ultimately into the Intergalactic Medium. Another example which we wish to discuss here in some more detail, involves the Galactic Wind which is partly driven by the GCRs themselves (e.g. Breitschwerdt et al., 1991, 1993; Zirakashvili et al., 1996). In fact, the wind velocity perpendicular to the disk - in z-direction - is much larger in the central regions of the Galaxy than at larger radii, through the radial variation of the Galactic gravitational field alone (see Fig. 2). This implies that for a given particle energy the boundary seperating the dominantly diffusive transport perpendicular to the Galactic disk near the disk from the dominantly convective transport at greater halo heights moves down in direction to the Galactic midplane in the inner Galaxy. Since the GCR diffusion coefficient increases with energy, the position of this boundary will depend on energy. As shown by
FIGURE 2. The terminal Galactic Wind velocity, and the base mass flux density, as functions of radius in the Galactic disk, cf. Breitschwerdt et al. (1991). All ISM parameters at the base of the wind were considered uniform. The radial variation of the Galactic gravitational field alone is sufficient to produce this radial gradient

Ptuskin et al. (1997), the energy spectrum of the GCRs is typically $\propto E^{-1.9}$ in the convection region compared to the standard spectrum $\propto E^{-2.7}$ in the diffusive confinement region of volume $V_c$ discussed in subsection 2.1. A line of sight that intersects this boundary will therefore receive gamma rays from two regions of very different GCR energy spectra, emitting correspondingly harder spectra than does the diffusive confinement region alone. Qualitatively this implies a hardening of the truly diffuse $\gamma$-ray spectrum with Galactic longitude towards the inner Galaxy, for given latitude. However, the effect will disappear for high enough energies when the convective zone does no more extend into regions of significant gas density.

Thus, in contrast to the contribution of the sources, this transport effect looses importance at high energies.

It remains to work out this effect quantitatively. But its very existence illustrates the interest we should attach to the measurements of the diffuse Galactic $\gamma$-ray emission over an as wide as possible range of energies.

CONCLUSIONS

The foregoing discussion shows that there are at least two mechanisms of basic physical interest that contribute to a deviation of the diffuse Galactic $\gamma$-ray emission
spectrum from what would be expected from CR observations in the Solar vicinity. The contribution from the SCRs is an inevitable one and is essentially sufficient to explain the data at least for the inner Galaxy; it should be part of the γ-ray emission model to begin with. Clearly this does not rule out effects from potentially existing new populations of CRs, especially electrons, or the influence of an increased strength, for instance, of the Interstellar radiation field. This is particularly true for high Galactic latitudes.

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