

# Limits for an inverse bremsstrahlung origin of the diffuse Galactic soft gamma-ray emission

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**Abstract.** RXTE, GINGA, and OSSE observations have revealed an intense low-energy  $\gamma$ -ray continuum emission from the Galactic plane, which is commonly interpreted as evidence for the possible existence of a strong flux of low-energy cosmic ray electrons. In this Paper I discuss the scenario of a hadronic origin of the soft Galactic  $\gamma$ -ray continuum through inverse bremsstrahlung.

A flux of low-energy cosmic rays strong enough to produce the observed spectrum of  $\gamma$ -rays implies substantial  $\gamma$ -ray emission at a few MeV through nuclear de-excitation. It is shown that the existing limits on excess 3-7 MeV emission from the Galactic plane, in concert with the constraints from  $\pi^0$ -decay  $\gamma$ -ray emission at higher energies, are in serious conflict with an inverse bremsstrahlung origin of the Galactic soft  $\gamma$ -ray emission for any physically plausible low-energy cosmic ray spectrum. While in case of energetic heavy nuclei the limits are violated by about an order of magnitude, for a large population of low-energy protons the implied  $\gamma$ -ray line flux and  $\pi^0$ -decay continuum intensity are larger than the existing limits by at least a factor of 2.

**Key words:** acceleration of particles – radiation mechanisms: non-thermal – cosmic rays – gamma rays: theory

## 1. Introduction

The Galactic plane is an extended source of  $\gamma$ -radiation. This has been shown at energies  $> 50$  MeV with SAS 2 (Hartman et al. 1979), COS-B (Strong et al. 1988), and most recently with EGRET (Hunter et al. 1997). Observations made with COMPTEL have demonstrated that this emission extends down to energies near 1 MeV (Strong et al. 1996). The diffuse Galactic  $\gamma$ -ray continuum at energies below 1 MeV is less well determined which is primarily due to the presence of a number of point sources, many of which are variable. In an analysis of Galactic plane observations made with OSSE (Purcell et al. 1996), it was found that, when the contribution from the prominent point sources monitored during simultaneous observations with SIGMA is subtracted from the Galactic center spectrum measured with OSSE, the diffuse emission is essentially identical to

that measured at  $l = 25^\circ$ . The residual intensity is roughly constant over the central radian of the Galaxy, but is lower by a factor 4 at  $l \approx 95^\circ$  (Skibo et al. 1997). If the residual emission is due to discrete sources, 10 sources of flux  $5 \cdot 10^{-3}$  ph./cm<sup>2</sup>/sec/MeV at 100 keV must be present in the field of view of OSSE to make up the spectrum. Because no such class of sources with a uniform space density in longitude is known, the emission at about 100 keV is probably of diffuse origin. Estimates based on the luminosities and number-flux distributions of galactic sources indicate that the point source contribution to the hard X-ray emission from the Galactic plane is less than 20% (Yamasaki et al. 1997; Kaneda 1997). Similar results have been found in an analysis of GRIS data (Gehrels et al. 1991). The residual source-subtracted spectrum of this emission changes from a photon index  $\alpha = 1.7$  at energies above 200 keV (Strong et al. 1994) to a photon index  $\alpha = 2.7$  at lower energies (Purcell et al. 1996). Thus the soft  $\gamma$ -ray continuum from the Galactic plane is more intense than the extrapolation of the higher energy emission. Observations of the Galactic ridge in the hard X-ray range with GINGA (Yamasaki et al. 1997) and RXTE (Valinia & Marshall 1998) indicate that the soft spectrum below 200 keV extends down to about 10 keV energy, though the best spectral fit between 15 keV and 150 keV gives a photon index of  $\alpha = 2.3$ . The spectrum may also be represented by an exponentially absorbed power-law of index  $\sim 1.7$  and cut-off energy  $\sim 130$  keV (Kinzer et al. 1998).

In previous papers electron bremsstrahlung has been considered the most likely source of the soft  $\gamma$ -ray continuum. The power in cosmic ray electrons required to produce a given amount of bremsstrahlung is a fixed quantity that depends only on the energy spectrum of the radiating electrons and weakly on the ionization state of the interstellar medium. Attributing this power input to injection in cosmic ray electron sources it has been estimated that a power of  $10^{42} - 10^{43}$  ergs sec<sup>-1</sup> in low-energy electrons is required, to maintain them against severe Coulomb and ionization losses (Skibo et al. 1996). This electron power exceeds the power supplied to cosmic ray nuclei by an order of magnitude. The energy losses of the required large population of low-energy electrons would be more than adequate to account for the observed hydrogen ionization rate in the interstellar medium (Valinia & Marshall 1998). Understanding the Galactic continuum emission below 1 MeV is therefore

of utmost importance to pin down the most relevant particle acceleration process and the ecosystem interstellar medium.

Recently, inverse bremsstrahlung (Boldt & Serlemitsos 1969) has been proposed as an alternative to electron bremsstrahlung as basic radiation process for the low-energy Galactic  $\gamma$ -ray continuum (Valinia & Marshall 1998). The source power required to maintain the radiating nucleons against the energy losses is similar to that in the case of electrons, but two aspects seem to be in favor of this scenario. First, the acceleration process does not need to favor electrons, thus shock acceleration or gyroresonant interactions with incompressive shear Alfvén waves could be invoked, similar to standard scenarios for solar flares (for a review see Ramaty & Murphy 1987). Second, the range of 50 MeV nucleons is about 1 g/cm<sup>2</sup> as opposed to 10<sup>-3</sup> g/cm<sup>2</sup> for 25 keV electrons (Berger & Selzer 1964), which allows nucleons to diffuse away from their sources and to cause radiation with the observed latitude distribution with 5° FWHM.

In this Paper I discuss the scenario of a hadronic origin of the soft Galactic  $\gamma$ -ray continuum in more detail. In the next section I calculate the emissivity for inverse bremsstrahlung and the nuclear excitation rate of low-energy cosmic ray nucleons. In the third section it is shown that even for very hybrid nucleon spectra the observed limits for nuclear  $\gamma$ -ray line emission and  $\pi^0$ -decay continuum emission are in conflict with an inverse bremsstrahlung origin of the Galactic low-energy  $\gamma$ -ray continuum.

## 2. Emission from low-energy nucleons

### 2.1. Inverse bremsstrahlung

The combined data of OSSE and RXTE of X-ray/ $\gamma$ -ray emission between 15 keV and 150 keV from the inner radian of the Galactic plane can be described by a differential photon spectrum (Valinia & Marshall 1998)

$$I(\epsilon) = (1.8 \cdot 10^{-3}) \epsilon^{-2.3} \quad (1)$$

where the photon energy  $\epsilon$  is in units of  $m_e c^2$  and all other units in cgs.

Let  $N(E) = N_0 E^{-s}$  be the differential spectrum of radiating nucleons over the range  $[E_1, E_2]$ , where  $E$  is in units of the particle's rest mass  $A m_p c^2$ . We may use the non-relativistic limit of the Bethe-Heitler cross section to write the cross section for inverse bremsstrahlung (Boldt & Serlemitsos 1969)

$$\epsilon \left( \frac{d\sigma}{d\epsilon} \right) = \frac{2\alpha Z^2 \sigma_T}{\pi E} \ln \left( \sqrt{\frac{E}{\epsilon}} + \sqrt{\frac{E}{\epsilon} - 1} \right) \quad (2)$$

where  $E \geq \epsilon$

The emissivity of inverse bremsstrahlung therefore is

$$\begin{aligned} \frac{dq}{d\epsilon} &= c n_e N_0 \int_{\max(\epsilon, E_1)} dE \beta E^{-s} \frac{d\sigma}{d\epsilon} \\ &= (10^{-16}) n_H Z^2 N_0 \epsilon^{-2.3} \end{aligned} \quad (3)$$

$$\text{for } E_1 \leq \epsilon \text{ and } n_e = \sum_{Z=1}^{26} n_Z Z \simeq 1.2 n_H$$

and the spectral index of radiating particles  $s = 1.8$ . By comparison with the observed flux (Eq. 1) we infer

$$N(E) = (1.8 \cdot 10^{13}) (C n_e)^{-1} Z^{-2} E^{-1.8}, \quad E \geq 0.03 \quad (4)$$

where the constant  $C$  describes the geometry. It is basically the ratio of flux from the inner radian and emissivity. Eq. 4 displays the differential number spectrum of a nucleon of charge number  $Z$ , that is required to make up the observed soft  $\gamma$ -ray continuum (Eq. 1) through inverse bremsstrahlung. Secondary electron bremsstrahlung contributes at a level of  $\lesssim 10\%$  to inverse bremsstrahlung for target material with solar abundance and is thus negligible (Abraham et al. 1966, Ramaty et al. 1997). In the next section I will calculate the flux of nuclear line emission produced by such a population of low-energy cosmic ray nuclei.

### 2.2. Nuclear excitation

The strongest contribution to Galactic  $\gamma$ -ray line emission can be expected from de-excitations of carbon nuclei at 4.4 MeV and oxygen nuclei at 6.1 MeV. The cross sections for nuclear excitation above 10 MeV/nuc. are roughly

$$\sigma(C) \simeq 3.1 \cdot 10^{-25} \left( \frac{E}{0.01} \right)^{-1.2} \text{ cm}^2 \quad (5)$$

$$\sigma(O) \simeq 1.6 \cdot 10^{-25} \left( \frac{E}{0.01} \right)^{-0.5} \text{ cm}^2 \quad (6)$$

where  $E$  is again in units of  $A m_p c^2$  (Ramaty et al. 1979). The flux of  $\gamma$ -ray line emission from the inner radian of the Galactic plane then is

$$I = \eta n_H c C \int dE \beta N(E) \sigma \quad (7)$$

where  $\eta$  is the abundance of the target material relative to that of hydrogen.

If the radiating particles are heavy nuclei, then the efficiency of inverse bremsstrahlung would be increased by the factor  $Z^2$  but the target material hydrogen would have an abundance  $\eta = 1$ , so that for a given flux of inverse bremsstrahlung energetic protons would produce roughly an order of magnitude less flux in  $\gamma$ -ray lines than do energetic Carbon or Oxygen nuclei. If only energetic carbon nuclei were responsible for the entire observed soft  $\gamma$ -ray continuum then the implied flux of  $\gamma$ -ray line emission from the inner radian of the Galactic plane would be

$$I_C \simeq 3.4 \cdot 10^{-3} \text{ ph./cm}^2/\text{sec} \quad (8)$$

Likewise we obtain for energetic oxygen nuclei

$$I_O \simeq 4 \cdot 10^{-3} \text{ ph./cm}^2/\text{sec} \quad (9)$$

Due to the smaller excitation cross sections the implied  $\gamma$ -ray line fluxes for other heavy nuclei would be lower, so that depending on the abundances of heavy nuclei in low-energy cosmic rays in the inner Galaxy an actual "average"  $\gamma$ -ray line flux would be  $\gtrsim 10^{-3}$  ph./cm<sup>2</sup>/sec.

If on the other hand a large population of low-energy protons is responsible for the soft  $\gamma$ -ray emission, then the implied flux of  $\gamma$ -ray line emission from the inner radian of the Galactic plane would be

$$I_H \simeq 2.6 \cdot 10^{-4} \text{ ph./cm}^2/\text{sec} \quad (10)$$

assuming a solar abundance of Carbon ( $\eta_C = 3.6 \cdot 10^{-4}$ ) and Oxygen ( $\eta_O = 8.5 \cdot 10^{-4}$ ) (Grevesse & Anders 1989). Note that these estimates for the  $\gamma$ -ray line flux have been calculated using the limits of the particle spectrum as in Eq. 4, i.e. assuming that no energetic particles exist with energies below  $E_1 = 0.03$ , and therefore they should be taken as lower limits.

If the low-energy protons are enriched by heavier nuclei with a differential intensity ratio corresponding to solar abundances, the estimate in Eq. 10 would be doubled and one would observe broad and narrow lines at similar flux levels.

### 3. Discussion

The results of the OSSE and COMPTEL experiments on  $\gamma$ -ray line emission following the de-excitation of carbon and oxygen nuclei are still preliminary. The OSSE team has reported a  $3\sigma$  upper limit for narrow lines from the inner radian of the Galactic plane (Harris et al. 1996)

$$I_{C,O}(\text{OSSE}) \leq 1.44 \cdot 10^{-4} \text{ ph./cm}^2/\text{sec} \quad (11)$$

For broad lines, i.e. energetic Carbon and Oxygen nuclei, the upper limit is about 50% higher. COMPTEL data have revealed some indication for an excess 3-7 MeV flux from the Galactic ridge at a level of (Bloemen & Bykov 1997, Bloemen et al. 1997)

$$I_{C,O}(\text{COMPTEL}) \lesssim 10^{-4} \text{ ph./cm}^2/\text{sec} \quad (12)$$

These limits strongly exclude a large population of low-energy heavy nuclei causing the observed soft  $\gamma$ -ray continuum. Inverse bremsstrahlung of protons seems to be weakly excluded as the implied  $\gamma$ -ray line flux is a factor of 2 higher than the  $3\sigma$  OSSE limit.

The main sources of uncertainty in the implied  $\gamma$ -ray line flux are: a) the abundance of Carbon and Oxygen in the inner Galaxy, b) the fraction of the soft  $\gamma$ -ray continuum which is truly diffuse emission, and c) the true low-energy limit of the power-law spectrum in Eq. 1.

The metallicity in the inner Galaxy is higher than in solar vicinity (Shaver et al. 1983), so that we can expect Carbon and Oxygen abundances to be higher than solar. This would lead to a higher  $\gamma$ -ray line flux and thereby increase the discrepancy between implied flux and the observational limits. The broad longitude distribution of the soft  $\gamma$ -ray continuum indicates that it is emitted roughly homogeneously throughout the Galactic

disk. In the remaining discussion we may therefore assume a metallicity like that near the molecular ring at about 4 kpc galactocentric radius, which is roughly a factor 2 higher than solar (Shaver et al. 1983).

The main contribution to the implied  $\gamma$ -ray line flux in Eq. 10 comes from excitations of ambient Oxygen nuclei. Due to the weak energy dependence of the Oxygen excitation cross section the  $\gamma$ -ray line flux depends on the lower limit of the proton spectrum roughly as  $\propto E_1^{-0.8}$ . Therefore, the predicted  $\gamma$ -ray line flux would harmonize with the observational limits only if  $E_1$  were  $\geq 0.1$ , which means that the continuum emission below 50 keV could not be entirely caused by inverse bremsstrahlung.

For energies above  $E=0.3$  the  $\gamma$ -ray continuum emission following pion production and decay provides another constraint on the number of energetic protons in the Galaxy. The combined data of EGRET, OSSE, and COMPTEL show that the  $\gamma$ -ray luminosity of the Galaxy at a few hundred MeV is about twice as much as that at 30 keV (Purcell et al. 1996). For protons with less than 100 MeV energy we can assume the Galaxy to act as a thick target (Pohl 1993), thus the particle spectrum is only determined by the energy losses. From the well-known energy dependence of Ionization and Coulomb losses (Heitler 1954; Butler & Birmingham 1962) we can infer that an  $Q \propto E^{-3.3}$  injection spectrum is required to maintain an  $N \propto E^{-1.8}$  equilibrium spectrum. The luminosity at a few hundred MeV photon energy then should scale to that at 30 keV like the ratio of the radiation efficiency times injected energy in the appropriate energy bands. Given the results for the mean density and escape lifetime of cosmic rays (Webber et al. 1992) we can estimate that for  $\pi^0$ -production  $\eta \simeq 0.02$ . For inverse bremsstrahlung at 30 keV the radiation efficiency can be calculated to be  $\eta \simeq 4 \cdot 10^{-5}$ . Therefore we obtain

$$\frac{L_\pi}{L_{IB}} = \frac{(\eta Q E^2)_\pi}{(\eta Q E^2)_{IB}} \simeq 20 \quad (13)$$

which exceeds the observed ratio of two by an order of magnitude. This implies that the proton spectrum (Eq. 4) would have to cut off sharply at energies near the pion production threshold of about  $E \simeq 0.3$ , corresponding to a cut-off in the inverse bremsstrahlung spectrum near 100 keV.

#### 3.1. Exponentially absorbed particle spectra

We have seen that the limits for  $\gamma$ -ray line emission constrain the particle spectrum at low energies whereas  $\gamma$ -ray continuum emission subsequent to pion production constrains at high energies. In this subsection I will investigate for two extreme cases if exponentially absorbed particle spectra can be found, which harmonize with both constraints *and* reproduce the observed soft  $\gamma$ -ray continuum via inverse bremsstrahlung emission. The abundances of Carbon and Oxygen will be assumed to be two times solar.

Suppose a proton spectrum of the form

$$N(E) = N_0 E^{-1} \exp(-3.3 E) \quad (14)$$

where the argument of the exponential has been chosen such as to reproduce the observed soft  $\gamma$ -ray continuum. The choice

of spectral form is entirely hybrid. If low-energy protons with a spectrum as in Eq. 14 were responsible for the observed soft  $\gamma$ -ray continuum via inverse bremsstrahlung then the implied  $\pi^0$ -decay  $\gamma$ -ray luminosity at a few hundred MeV would be 2.5 times that of the 30 keV inverse bremsstrahlung emission, roughly in accordance with the observed ratio of two. However, the narrow  $\gamma$ -ray line emission would have a flux of  $10^{-3}$  ph./cm<sup>2</sup>/sec, clearly above the observational limits. Thus the spectrum Eq. 14 would be too soft to harmonize with the low-energy constraints.

The flux of low-energy ( $E=0.01$ ) protons may be reduced if distinct sources provide an injection spectrum like Eq. 14 such that energy losses within the sources can be neglected. Then the overall particle spectrum would result from a balance equation for energy losses and injection (Eq. 14) as

$$N(E) = N_0 \sqrt{E} \int_E du u^{-1} \exp\left(-\frac{u}{0.25}\right) \quad (15)$$

where the argument of the exponential has been readjusted to reproduce the observed low-energy  $\gamma$ -ray spectrum. The implied narrow  $\gamma$ -ray line flux would be about  $2 \cdot 10^{-4}$  ph./cm<sup>2</sup>/sec, but the implied  $\pi^0$ -decay  $\gamma$ -ray luminosity at a few hundred MeV is 30 times that of the 30 keV continuum, clearly in conflict with the data.

An exponential cut-off in the low-energy proton spectrum seems to be insufficient to satisfy the constraints at low and high energy. Therefore only a quasi-monoenergetic injection of pure protons would harmonize with the data. I do not regard this a physically plausible scenario.

#### 4. Conclusions

An inverse bremsstrahlung origin of the intense soft Galactic  $\gamma$ -ray continuum emission implies substantial  $\gamma$ -ray line emission through nuclear de-excitation and it is thus testable.

The existing limits on Galactic  $\gamma$ -ray line emission exclude a large population of low-energy heavy nuclei.

For low-energy protons the current observational limits are in conflict with a large population of Galactic cosmic ray proton both below 40 MeV and above 400 MeV. It seems that no physically plausible proton spectrum can be constructed which would reproduce the observed low-energy  $\gamma$ -ray continuum via inverse bremsstrahlung emission and harmonize with the existing limits for nuclear  $\gamma$ -ray line emission and  $\pi^0$ -decay  $\gamma$ -ray emission.

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