Nonthermal X-Rays from the Galactic Ridge: a Tracer of Low Energy Cosmic Rays?

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Abstract.
A distinct low energy cosmic-ray component has been proposed to explain the essentially constant Be/Fe ratio at low metallicities. Atomic collisions of such low energy ions produce characteristic nonthermal X-ray emission. In this paper, we study the possible contribution of such X-rays to the Galactic ridge emission. We show that they would account for \( \lesssim 10\% \) of the 10-60 keV luminosity of the thin Galactic disk component detected with RXTE. They could make a more significant contribution in the 0.5-10 keV energy range, provided that the nonthermal ion population extends down to about 1 MeV/nucleon and delivers about \( 10^{42} \) erg s\(^{-1} \) to the interstellar medium, comparable to the total power supplied by the Galactic supernovae. But since the nonthermal X-rays in this energy range are essentially produced below the thresholds of the Be-producing cross sections, their detection does not necessarily imply a low energy cosmic-ray origin for the spallogenic light elements. A significant contribution of nonthermal X-rays could alleviate the problem of the origin of the hard component observed with ASCA in the Scutum arm region.

1. Introduction

The recent measurements of Be and B abundances in low metallicity stars (see Vangioni-Flam et al. 1998 for a recent compilation) shed new light on the origin of cosmic rays (Ramaty, Kozlovsky, & Lingenfelter 1998). A distinct Galaxy wide cosmic-ray component, accelerated out of fresh nucleosynthetic matter and predominant at low energies (\( \lesssim 100 \) MeV/nucleon), has been proposed to account for the quasi linear correlation between Be and Fe for [Fe/H]\(<-1 \) (Cassé, Lehoucq & Vangioni-Flam 1995; Ramaty, Kozlovsky & Lingenfelter 1996). Alternatively, it was suggested that the standard Galactic cosmic rays themselves are accelerated mostly out of supernova ejecta (Lingenfelter, Ramaty, & Kozlovsky 1998; Higdon, Lingenfelter, & Ramaty 1998). Nuclear gamma-ray line observations could distinguish between the models. Low energy cosmic rays (LECRs) also produce X-rays by a variety of processes (Tatischeff, Ramaty, &
Kozlovsky 1998 and references therein; Dogiel et al. 1998). Electron capture and excitation in low energy ions (typically in the energy range from a few tenths to several tens of MeV/nucleon) produce characteristic broad X-ray lines in the 0.5-10 keV energy range and K-shell vacancy creation in ambient heavy atoms by similar energy fast ions produce narrow X-ray lines also up to about 10 keV. In addition, ions of energies up to a few hundreds of MeV/nucleon produce X-ray continuum at energies of several tens of keV. X-ray observations, therefore, can provide further information, and also set constraints, on LECRs in the Galaxy.

The diffuse X-ray emission from the Galactic disk has been intensively studied since its first detection by Bleach et al. (1972). Yamauchi et al. (1996) and Kaneda et al. (1997) have argued, from deep ASCA observations of the Scutum arm region, that the bulk of the Galactic ridge X-ray emission (GRXE) is truly diffuse, as opposed to resulting from the superposition of unresolved point sources. The ASCA spectrum shows K lines from Mg, Si, S and Fe (at energies from about 1 to 9 keV), and has been modeled by a double-temperature non-equilibrium ionization plasma model with temperatures of kT~0.8 keV and kT~7 keV (Kaneda et al. 1997). The lower temperature emission could be associated with a population of supernova remnants and superbubbles in the Galactic disk (Kaneda et al. 1997; Valinia & Marshall 1998). The origin of the component at the higher plasma temperature, hereafter the hard component, is more problematic. In particular, it is difficult to explain how a ~7 keV plasma could be confined to a very low scale height (b~0.5°), as its temperature significantly exceeds the gravitational escape temperature (~0.4 keV) of the Galaxy.

The GRXE above 10 keV is clearly of nonthermal origin. A power law tail reaching 600 keV has been detected with Ginga and Welcome-1 (Yamasaki et al. 1997) as well as with OSSE (Skibo et al. 1997). Valinia & Marshall (1998) have recently performed a careful scan of the Galactic plane with RXTE. They extract two spatial components from the GRXE in the 2-60 keV energy range: a thin disk of width <0.5° and a broad component whose latitude distribution is approximated by a Gaussian of ~4° FWHM. They discuss the origin of the >10 keV X-rays in the two spatial components in terms of unresolved discrete sources, inverse Compton scattering and bremsstrahlung of fast electrons, as well as inverse bremsstrahlung from energetic protons.

In this paper we present calculations that demonstrate the relationship between the Be production and the X-ray and nuclear gamma-ray line productions, and we investigate the possible contribution of nonthermal ion interactions to the GRXE. We use the constraint set by the essentially constant Be/Fe ratio at low metallicities on the current epoch Be production (Ramaty et al. 1997) to calculate the expected X-ray luminosity from nonthermal ion interactions. We compare it with the observed luminosities of the two spatial components detected with RXTE and with the luminosity of the hard component in the ASCA energy band. We also calculate the expected 3-7 MeV nuclear gamma-ray line flux from the central radian of the Galaxy. In agreement with previous calculations (Ramaty et al. 1997), we show that this emission would be only marginally detectable with INTEGRAL.
2. Interaction model

We perform the calculations in a steady state, thick target model in which accelerated particles, injected at a constant rate, interact with a neutral ambient medium of solar composition. The gamma-ray line, Be and X-ray productions are calculated as in Ramaty et al. (1996; 1997) and Tatischeff et al. (1998), respectively. We employ three different compositions for the fast ions: CRS and CRS\textsubscript{metal} (Ramaty et al. 1997) and OB\textsubscript{IG} (Parizot, Cassé & Vangioni-Flam 1997, table 1, the OB/0.04 column). CRS is the composition of the current epoch Galactic cosmic-ray sources; CRS\textsubscript{metal} is identical to CRS, but without protons and α particles. OB\textsubscript{IG} is the calculated average composition of the stellar winds from OB associations in the inner Galaxy; the O-to-proton ratio for this composition is similar to the corresponding ratio for the CRS composition, but the abundances of Mg, Si, S and Fe relative to protons are lower.

As the X-ray line production is sensitive to very low energy ions (near 1 MeV/nucleon), we replace the previously used ion spectra (Ramaty et al. 1996), which were quite flat at low energies, with an accelerated ion source spectrum given by a power law in kinetic energy:

$$q_i(E) \propto E^{-s} \text{ for } 1 \text{ MeV/nucleon} < E < 10^3 \text{ MeV/nucleon.}$$

The corresponding power is

$$\dot{W} = \sum_i A_i \int E q_i(E) dE,$$

where $A_i$ is the nuclear mass for particle species $i$. 

![Predicted X-ray luminosities](image)
We normalize both X-ray and gamma-ray line productions to the instantaneous Galaxy-wide Be production rate (Ramaty et al. 1997)

\[
\dot{Q}(Be) = \frac{Be}{Fe} \times \frac{M_{SNII}(Fe)}{56m_p} \times \dot{S}N = 3 \times 10^{39} \text{ atoms s}^{-1}.
\]

Here, \(Be/Fe=1.45 \times 10^{-6}\) is the best fit constant value (Vangioni-Flam et al. 1998) to the observed abundance ratio for \([Fe/H]<-1;\) \(M_{SNII}(Fe)=0.1 M_\odot\) is the average Fe production yield per core-collapse supernova (Ramaty & Lingenfelter 1998); \(m_p\) is the proton mass; and \(\dot{S}N=3\) per century is the current epoch Galactic supernova rate.

3. Results

The calculated nonthermal X-ray luminosities are shown in Figure 1. In the 10-60 keV energy range (Fig. 1a), the bulk of the emission is due to inverse bremsstrahlung (Tatischeff et al. 1998) and radiative electron capture (REC) on fast Fe (Tatischeff & Ramaty 1999). REC is the dominant emission process for the CRS composition and \(s>4.3\), and for the CRS\textsubscript{metal} composition and \(s>3.2\). It is less important for the OB\textsubscript{IG} composition which, as just mentioned, is more impoverished in Fe. As both Be-atoms and 10-60 keV X-rays are essentially produced by ions of the same energies, the calculated luminosities are not very dependent on the source spectrum. They range from \(5.1 \times 10^{35} \) to \(1.5 \times 10^{36} \) erg s\(^{-1}\) for the CRS composition, \(2.1 \times 10^{35} \) to \(7.1 \times 10^{35} \) erg s\(^{-1}\) for CRS\textsubscript{metal} composition, and \(1.2 \times 10^{35} \) to \(1.1 \times 10^{36} \) erg s\(^{-1}\) for OB\textsubscript{IG} composition (Fig. 1a). Valinia & Marshall (1998) estimated the luminosities of the GRXE in the 10-60 keV band to be \(1.5 \times 10^{38} \) erg s\(^{-1}\) and \(10^{37} \) erg s\(^{-1}\) for the broad component and the thin disk, respectively. We thus conclude that nonthermal X-ray production from fast ion interactions is probably not the main Galactic ridge emission in the 10-60 keV energy range, unless the X-rays are produced in source regions in which the Be is either destroyed or prevented from escaping to the interstellar medium.

The calculated X-ray luminosities in the 0.5-10 keV energy range are rapidly increasing functions of the source spectrum index (Fig. 1b). Indeed, the X-rays in this energy range are essentially produced at low energies, below the thresholds of the Be-producing spallation cross sections. We see that for \(3<s<3.5\), nonthermal X-rays could account for most of the hard component detected with ASCA in the 0.5-10 keV energy range (Kaneda et al. 1997). We note, however, that the estimated luminosity of this component, \(2 \times 10^{38} \) erg s\(^{-1}\) (Kaneda et al. 1997), is model dependent. It has been evaluated under the assumption of a very hot plasma origin, and after removing the photoelectric absorption in the ASCA data analysis. As a significant fraction of this luminosity is contained in low energy X-rays, which are not detected because they are completely absorbed in the Galactic plane, its value could be different if part of the emission is of nonthermal origin.

Figure 2 shows the LECR power deposition into the interstellar medium that accompanies the production of \(2 \times 10^{38} \) erg s\(^{-1}\) in the 0.5-10 keV energy range, the estimated X-ray luminosity of the hard component observed with
Figure 2. Power in LECRs required to produce the estimated luminosity of the hard component detected with *ASCA* in the 0.5-10 keV energy range, $2 \times 10^{38}$ erg s$^{-1}$ (Kaneda et al. 1997). For $s > 3$, 90% of the calculated power resides in <10 MeV/nucleon particles. Also shown is the power in supernova ejecta (eq. 3).

*ASCA*. Also shown is the power delivered by Galactic supernovae,

$$\dot{W}_{SN} = E_{SN} \times \dot{S}N = 1.5 \times 10^{42} \text{ erg s}^{-1},$$  

where $E_{SN}=1.5 \times 10^{51}$ erg is the approximate total ejecta kinetic energy of a supernova (Woosley & Weaver 1995). LECRs with CRS$_{metal}$ composition are the most efficient soft X-ray emitters, because they produce intense line emission from electron capture and excitation in 1-10 MeV/nucleon ions. We see that for this composition and $3 < s < 3.5$, the required LECR power amounts to about 30% of the available power in supernova ejecta, allowing a reasonable LECR acceleration efficiency. We note that the required acceleration is very modest, since the bulk of the X-rays are produced by nuclei below about 10 MeV/nucleon, and indeed the bulk of the LECR power also resides in such very low energy particles. It is thus possible that the hard component observed with *ASCA* is due to nonthermal ions. Of the three assumed compositions, on grounds of energetics, CRS$_{metal}$ appears to be the most promising.

Calculated nonthermal X-ray emissions are shown in Figures 3a and b for the CRS$_{metal}$ and OB$_{IG}$ compositions, respectively. We took into account photoelectric absorption with $N_H=4.6 \times 10^{22}$ cm$^{-2}$, the absorbing H column density of the hard component in the *ASCA* energy band (Kaneda et al. 1997). The narrow lines are due to K-shell vacancy production in the ambient atoms by the fast ions (Tatischeff et al. 1998). The broad line features, prominent in Fig.
3a, are due to atomic de-excitation in the fast ions following charge exchange (i.e. electron capture) and atomic excitation. The detection of these broad lines would constitute an unequivocal signature of LECRs in the Galaxy. Thus, the broad feature between 5.5 and 9 keV in Fig. 3a would trace the interactions of $\sim 10$ MeV/nucleon Fe (Tatischeff et al. 1998). However, this excess is nearly absent in Fig. 3b. We see that for the OB$_{IG}$ composition, which is more impoverished in Mg, Si, S and Fe, only the narrow lines from de-excitations in the ambient atoms could be observed.

These narrow lines, due to K-shell vacancy production by ion impacts, can be distinguished from the X-ray lines produced in a hot ionization equilibrium plasma, because their line energies are different, e.g. the Fe K$\alpha$ line is at 6.40 keV following proton impact in a neutral medium while it is at 6.97 and 6.70 keV for H- and He-like Fe in a 7 keV plasma. However, Kaneda et al (1997) have shown that the hard component detected with ASCA cannot be explained by a hot plasma at ionization equilibrium, because the centroid energy of the observed Fe line is lower than 6.70 keV. More detailed spectral analyses of the ASCA data could provide further constrains on the possible contribution of nonthermal X-ray line emission. A fundamental problem is to distinguish the lines produced by ion impacts from fluorescent lines, as the K-shell vacancies created by protons and X-rays lead to line emission at the same energies. However, for heavy ion collisions, the ion impact lines could be shifted by several tens of electron-volts, significantly broadened and splitted up into several components, owing to multiple simultaneous ionizations (Garcia, Fortner & Kavanagh 1973). For
example, the Fe K$_\alpha$ line produced by 1.9 MeV/nucleon O impacts is blueshifted by $\sim$50 eV in comparison with that produced by proton impacts, and has a FWHM of $\sim$100 eV (Garcia et al. 1973, figure 3.55). It may thus be possible with future fine spectroscopic analyses to obtain the necessary signatures to establish the existence of narrow lines produced by LECRs.

Finally, we calculated the 3-7 MeV nuclear gamma-ray line emission that would accompany both Be and X-ray productions. The results are shown in Figure 4. The predicted fluxes are compared with the upper limits obtained with OSSE for both broad and narrow line emissions from the central radian of the Galaxy (Harris et al. 1996). We used the same spatial model as Ramaty et al. (1997):

$$F_\gamma(3-7 \text{ MeV}) = \zeta 10^{-46} \dot{Q}_\gamma(3-7 \text{ MeV}) \text{ (photons cm}^{-2} \text{ s}^{-1} \text{ rad}^{-1})$$  \hspace{1cm} (4)$$

with $\zeta=1$. The total gamma-ray production rate $\dot{Q}_\gamma(3-7 \text{ MeV})$ is normalized to the Be production of $3 \times 10^{39}$ atoms s$^{-1}$ (eq. 2). We see that for $s<3.5$, which is the allowed range of spectral index in order to not overproduce the Galactic ridge soft X-ray emission (Fig. 1b), the calculated gamma-ray line fluxes are lower than $5 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ rad$^{-1}$. Similar results were
obtained by Ramaty et al. (1997) using different source spectra. Unfortunately, this diffuse 3-7 MeV emission should be difficult to detect with the *INTEGRAL* spectrometer (Schönfelder, this conference).

4. Discussion

Soft X-ray observations constitute an alternative and promising way of tracing LECRs in the Galaxy. We have shown that the distinct Galaxy wide LECR component, which has been proposed to explain the recent Be abundance observations at low metallicities, could account for the hard component of the GRXE in the 0.5-10 keV energy domain, provided that the LECR spectrum extends as an unbroken power law down to about 1 MeV/nucleon, implying that the power in the accelerated particles is about $10^{42}$ erg s$^{-1}$. On the other hand, as the nonthermal X-rays in this energy range are essentially produced below the thresholds of the Be-producing cross sections, their detection would not ipso facto imply a LECR origin for the spallogenic light elements.

However, as the expected nonthermal X-ray production is probably not the dominant emission in the 10-60 keV energy range, it may not be the main emission in the 0.5-10 keV energy range, as well. A large population of low energy electrons, which could result from efficient reacceleration of cosmic rays by interstellar plasma turbulences (Schlickeiser 1997) may also contribute to the Galactic ridge soft X-ray emission. In any case, it is important to emphasize that the detection of K lines with *ASCA* does not prove that the 0.5-10 keV GXRE is of thermal origin, since interactions of accelerated ions could also produce intense K line emission. In particular, the very low scale height of the hard component detected with *ASCA* may be better understood if the emission is of nonthermal origin. As suggested by Parizot (1998), LECRs could be efficiently accelerated in superbubbles associated with giant molecular cloud OB associations. In this model, we would expect the nonthermal X-rays to be essentially produced at dense molecular cloud boundaries, and thus the Galactic X-ray emission to be correlated with the thin CO emission, which traces the molecular hydrogen.

There are now evidences from both *ASCA* and RXTE surveys that the diffuse X-ray emission from the Galactic plane has multiple origins. More detailed spectral analyses of *ASCA* and future XMM data are required to constrain a possible contribution of nonthermal ion interactions to the soft X-ray emission and thus the eventual existence of a distinct low energy cosmic ray component in the Galaxy.

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