A&A 382, 730–745 (2002)
DOI: 10.1051/0004-6361:20011632

Astronomy & Astrophysics

Nonthermal hard X-ray emission from the Galactic Ridge

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Received 28 February 2001 / Accepted 15 November 2001

Abstract. We investigate the origin of the nonthermal X-ray emission from the Galactic ridge in the range 10−200 keV. We consider bremsstrahlung of subrelativistic cosmic ray protons and electrons as production processes. From the solution of the kinetic equations describing the processes of particle in situ acceleration and spatial propagation we derive parameters of the spectra for protons and electrons. It is shown that the spectra must be very hard and have a cut-off at an energy $\sim$150−500 MeV for protons or $\leq$300 keV for electrons. For in situ acceleration the flux of accelerated particles consists mainly of protons since the ratio of the accelerated protons to electrons is large and the flux of nuclei with charges $Z > 1$ is strongly suppressed. We show that the gamma-ray line flux generated by protons does not exceed the upper limit derived from observations if we assume that the X-ray ridge emission is due to proton bremsstrahlung. However, the flux of π° photons produced by the accelerated protons is higher than the observed flux from the Galactic ridge if the cut-off is exponential for $\geq$150 MeV. If the cut-off in the spectrum is extremely steep its value can be as large as 400 MeV, just near the threshold energy for π° photon production. In this case the flux of gamma-rays is negligible but these protons still produce X-rays up to 200 keV. If a significant part of the hard X-ray emission at energies $\sim$100 keV is emitted by unresolved sources, then the energy of X-rays produced by the protons does not have to exceed several tens keV. Therefore, the cut-off energy can be as small as 30−50 MeV and in this case the flux of π° photons is negligible too. But for small cutoff energies the flux of nuclear gamma-ray lines exceeds significantly the upper limit derived from the COMPTEL and OSSE data. Hence the cut-off of the proton spectrum has to be somewhere in between 50−150 MeV in order not to exceed both π° and gamma-ray line fluxes. However the energy density of the CR protons would have to be $\sim$400 eV cm^{-3} which seems implausible. If on the contrary the hard X-ray emission from the disk is emitted by accelerated electrons we do not have the problems of gamma-ray line and π° fluxes at all, and the required energy density of particles is only $\sim$0.2 eV cm^{-3}. But in this case we must assume that acceleration of protons is suppressed. We discuss briefly the possible origin of this effect. We have also estimated the ionization rate produced by the accelerated particles in the interstellar medium, and it is found that ionization of the medium would be very significant for both energetic protons and electrons. In this way we may perhaps resolve the problem of the observed large ionization rate.

Key words. acceleration of particles – galaxy: general – ISM: cosmic rays – radiation mechanisms: non thermal

1. Introduction

The diffuse emission from the Galactic ridge has been observed over a very broad energy range – from the radio to the gamma-ray band.The origin of the radio and gamma-ray emission is more or less clear[1]. It is mostly nonthermal and produced by relativistic electrons and nuclei which interact with the interstellar magnetic field, background gas and low energy photons. An important point is that the cosmic ray (CR) luminosity needed to produce this emission can be derived directly from observational data, and it is almost model independent (see Berezinskii et al. 1990)

$$L_{\rm cr} \sim \frac{W_{\rm cr}}{t_{\rm cr}} = \frac{cw_{\rm cr}\rho V}{\rho c t_{\rm cr}} = \frac{cw_{\rm cr}M_{\rm g}}{x} \sim 5\times 10^{40}\ {\rm erg\ s}^{-1}. \quad (1)$$

Here:
$w_{\rm cr}$ is the CR energy density measured near Earth;
V is the volume of the Galaxy filled with CRs;
$W_{\rm cr} \sim w_{\rm cr}V$ is the total energy of Galactic CRs:
$t_{\rm cr}$ is the CR lifetime;
ρ is the average gas density in the Galaxy;
$M_{\rm g} \sim \rho V$ is the total gas mass in the Galaxy determined from radio data;

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[1] Though the excesses of the diffuse gamma-ray emission observed in the energy ranges below 30 MeV (Strong et al. 2000) and above 1 GeV (Hunter et al. 1997) are inconsistent with the standard parameters used in models of cosmic ray origin.

$x \sim \rho c t_{\rm cr}$ is the grammage traversed by cosmic rays in the Galaxy which is determined from the CR chemical composition near Earth.

The necessary energy for CR production can be supplied by supernovae (SN) (see Ginzburg & Syrovatskii 1964). Indeed, the average energy release of a supernova explosion is about of 10^{50-51} erg, which occurs every 30−100 years in the Galaxy. Then the average supernova power is about

$$L_{\rm SN} \sim 10^{41-42} \text{ erg s}^{-1}. \quad (2)$$

Therefore ∼10% of the explosion energy should be transformed into the energy of fast particles to maintain the CR Galactic luminosity. This can be realized in processes of particle acceleration by SN shocks (see, e.g., Berezhko et al. 1994). This model of CR production by SNs successfully describes the characteristics of the diffuse radio and gamma-ray emission from the Galaxy (Berezinskii et al. 1990, see also Strong et al. 2000). Indeed, the total energy flux of gamma-ray emission produced by the proton CR component in the galactic disk is $L_\gamma \sim 10^{39}$ erg s^{-1}. From this value the necessary flux of CRs $L_{\rm cr}$ can be estimated from

$$L_{\rm cr} \sim L_\gamma \frac{x_\gamma}{x}, \quad (3)$$

where x_γ is the matter thickness needed to produce a gamma-ray photon, $x_\gamma \simeq 120$ gr cm^{-2}, and x is the grammage traversed by CRs in the Galaxy, $x \simeq 12$ gr cm^{-2}. Then from Eq. (3) we obtain that the CR energy flux which produce galactic gamma-rays is $L_{\rm cr} \sim 10^{40}$ erg s^{-1} that is in agreement with the value (1).

However, attempts to extend this model to the region of the nonthermal hard X-ray band (below 100 keV) have serious problems. According to measurements of the nonthermal spectrum of the diffuse emission by OSSE (Kinzer et al. 1999) and GINGA (Yamasaki et al. 1997) the nonthermal X-ray flux in the energy range above 10 keV is $L_x \sim 10^{38}$ erg s^{-1}. If the 10 keV nonthermal emission is due to electron bremsstrahlung (see Skibo et al. 1997) the necessary energy flux can be estimated as

$$L_{\rm cr} \sim L_x \frac{\tau_x}{\tau_{\rm i}}, \quad (4)$$

where τ_x is the characteristic time for production of bremsstrahlung photons and $\tau_{\rm i}$ is the characteristic lifetime of the electrons due to ionization losses. The ratio $\tau_x/\tau_{\rm i} \sim 10^5$ then from Eq. (4) we obtain that the CR luminosity is about 10^{43} erg s^{-1} This is much more than the value (1) and even more than what can be supplied by SNs (2).

In this respect it is reasonable to assume that there may be two sources of CRs in the Galaxy: SNR which produce particles in the relativistic energy range up to 10^{14}–10^{17} eV and another unknown very powerful source which generates subrelativistic particles. Below we discuss this problem in more detail. We start from the observational data.

2. Observational data

Analysis of the observed X-ray flux in the range 2–16 keV with the GINGA satellite (Yamasaki et al. 1997) showed that there is a hard component in the ridge spectrum in addition to the hot plasma component (see Fig. 1). The total estimated luminosity is around 2×10^{38} erg s^{-1} in the 3−16 keV energy range. The combination of the GINGA spectrum with measurements at higher energies shows that the emission spectrum can be represented as a power-law over a very broad energy band without any flattening in the low energy range due to ionization losses. This means that the X-ray flux is produced in regions where the electrons are still freshly accelerated.

Observations with the RXTE telescope also show a hard X-ray excess above the thermal emission (Valinia & Marshall 1998).

Analysis of the ASCA data (the energy range 0.5−10 keV) led to the conclusion that this emission cannot be due to unresolved point-like sources since a class of sources with the required properties is not known and in fact can be excluded (Tanaka et al. 1999). Hence the emission is most likely of diffuse origin.

The diffuse flux can be produced either by emission by a hot plasma with a temperature >7 keV or by fast (nonthermal) particles. The thermal origin of the emission seems to be doubtful since: 1) it is not clear how to explain the plasma confinement in the disk because the thermal velocity in this case exceeds significantly the escape velocity from the Galactic plane, 2) if the plasma is heated by supernova explosions, this assumption requires a too large SN explosion rate of one per several years (see, e.g., Yamasaki et al. 1997), 3) the width of X-ray lines observed in the direction of the Galactic ridge far exceeds that expected for the case of thermal broadening (Tanaka et al. 2000). All these facts cast doubt on a thermal origin of the observed X-ray spectrum.

Another candidate for hard X-ray production in the Galactic ridge could be extended discrete sources like supernova remnants (SNRs). If the angular size of these remnants exceeds 1°, an ensemble of these SNRs may overlap with each other and form a smooth brightness distribution indistinguishable from truly diffuse emission. Analysis of the SNR bremsstrahlung X-ray emission has been performed by Baring et al. (2000) who showed that a significant flux of hard X-rays is generated by electron bremsstrahlung in a so-called "Coulomb halo" around SNR whose maximal extent for 24 keV electrons is 100 pc. This shell-connected emission dominates the volume-integrated emission from SNR environs out to 100 pc from the centre of SNRs. If the density of SNRs were high enough (the filling factor should be higher than 10^{-4}–10^{-3}) the truly diffuse interstellar emission would be obscured by the emission of the SNR X-ray halos. In this case the major contribution to unresolved diffuse X-ray emission of the Galactic ridge would come from these discrete extended sources. However, the most optimistic estimates of the SNR filling factor lead to the lower part of this range. Thus, Koyama et al. (1986) showed that the SNR remnant scenario of the hard X-ray origin requires an unbelievably high supernova frequency, as high as one every 10 years (see also Yamauchi et al. 1996 and Kaneda et al. 1997). The flux of an individual "Coulomb halo" for the total ridge flux 2×10^{38} erg s^{-1} in the energy range 2−16 keV is of the order $\geq 10^{35}$ erg s^{-1} for about one thousand SNRs in the central region of the galactic disk. However, there have been only a few detections of SNRs having such a very high temperature (>2 keV) and a such high luminosity ($\sim 10^{35}$ erg s^{-1}). The recent CHANDRA results have confirmed that the hard X-ray emission of the Galactic ridge is truly diffuse (Ebisawa et al. 2001).

Hence, among several candidates for the hard X-ray Galactic ridge flux only the truly diffuse emission has remained.

Thus, from the observations of the GINGA, RXTE and ASCA telescopes it follows that the hard X-ray emission is diffuse and nonthermal at least up to 16 keV.

Little is also known about the origin of the diffuse ridge emission at higher X-ray energies. This energy range was investigated with OSSE (Kinzer et al. 1999), WELCOME-1 (Yamasaki et al. 1997) and RXTE (Valinia & Marshall 1998). A difficult task for these experiments is to distinguish the diffuse emission from that of unresolved sources. From the OSSE observations it follows that there are at least three components in the central ridge continuum spectrum below 1 MeV: a variable soft component which contains strong contributions from discrete sources; a positronium continuum; and a significant part of the emission which may be due to CR interaction with the gas and photons although there are certainly further contributions from weaker sources. The spectrum of the diffuse emission is flat below 35 keV. However above this energy there is a significant steepening in the spectrum. The spectrum in the range 10−400 keV is at best described by an exponentially cutoff power-law of the form (Valinia et al. 2000a)

$$I_x \propto E_x^{-0.6} \exp(-E_x/40 \text{ keV}), \tag{5}$$

i.e. the spectrum of the hard X-rays cuts off above 40 keV. Thus, it is reasonable to assume that there are at least three components of the diffuse emission in the Galactic disk: the hot background plasma emitting the ridge thermal emission and peaked at 3 keV, a process emitting hard X-rays above 10 keV, and SNRs which accelerate the Galactic cosmic rays generating the diffuse gamma-ray emission.

The existence of these components can be seen in Fig. 1 which shows the total ridge spectrum for X-rays and gamma-rays.

The ridge X-ray emission in the range 10−16 keV is definitely diffuse and nonthermal. The origin of the emission at higher energies up to several hundred keV is not clear but there are reasonable arguments that it is also diffuse and nonthermal although the fraction of the emission contributed by discrete sources is unknown.

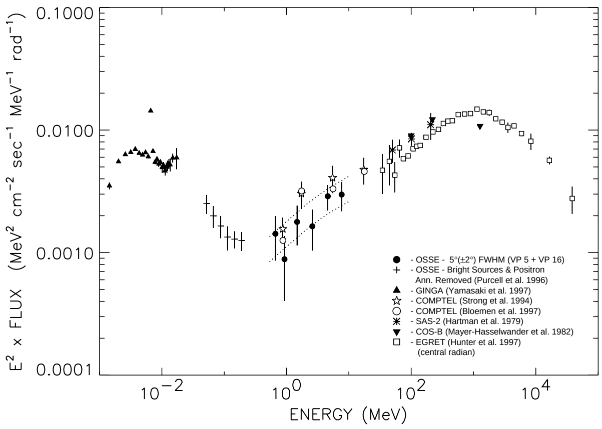

Fig. 1. The spectrum of diffuse emission from the Galactic disk (this figure was taken from Kinzer et al. 1999).

It is worth mentioning that this excess of hard X-ray emission observed in the Galaxy is not unique. An excess of hard X-rays above the thermal flux has been observed in the spectra of the galaxy clusters Virgo (Lea et al. 1981) and Coma (Fusco-Femiano et al. 1999); this has been interpreted as a result of particle in situ acceleration in the intracluster medium (see, e.g., Enßlin et al. 1999; Dogiel 2000; Sarazin & Kempner 2000).

Various models for the nonthermal origin of the ridge excess have been presented. They include: inverse Compton scattering of relativistic electrons, bremsstrahlung radiation of subrelativistic electrons or protons. As Skibo et al. (1996) showed, however, the IC scattering of relativistic electrons cannot produce the bulk of hard X-ray emission below 100 keV since these electrons generate also a flux of radio emission which is higher than that observed. In this paper we discuss two other mechanisms: electron bremsstrahlung and proton bremsstrahlung (or inverse bremsstrahlung).

3. The energy and particle outputs in emitting particles

The bremsstrahlung photon production Q_x by parent particles with production rate Q can be estimated as

$$Q_x \sim Q \cdot \frac{\tau_l}{\tau_{\rm br}} \text{ (particles s}^{-1}\text{)}, \tag{6}$$

where τ_l is the lifetime of the emitting particles which in our case is determined by Coulomb collisions (if the particles do not escape from the emitting region), and $\tau_{\rm br}$ is the characteristic time for the production of X-ray photons by bremsstrahlung.

The bremsstrahlung cross-section for production of a photon with energy E_x by electrons or protons can be written in the form (see e.g. Hayakawa 1969)

$$\frac{{\rm d}\sigma_{\rm br}}{{\rm d}E_x} = \frac{8}{3} Z^2 \frac{e^2}{\hbar c} \left(\frac{e^2}{mc^2}\right)^2 \frac{mc^2}{E'} \frac{1}{E_x} \times \ln \frac{\left(\sqrt{E'} + \sqrt{E' - E_x}\right)^2}{E_x}. \tag{7}$$

Here we should take $E' = E_{\rm e}$ for electrons where $E_{\rm e}$ is the electron kinetic energy, and $E' = (m/M)E_{\rm p}$ for protons where $E_{\rm p}$ is the proton kinetic energy, since a photon with energy E_x can be produced either by an electron with energy $E_{\rm e} \sim E_x$ or by a proton with energy $E_{\rm p} \sim (M/m)E_x$; here m and M are the electron and proton rest masses (see in this respect estimations of expected X-ray fluxes from Orion produced by subrelativistic electrons and protons presented in Dogiel et al. 1997, 1998).

The flux of bremsstrahlung photons is in this case

$$Q_x = \int N(E) nv \frac{{\rm d}\sigma_{\rm br}(E, E_x)}{{\rm d}E_x} {\rm d}E. \tag{8}$$

The time $\tau_{\rm br}$ from Eq. (6) is

$$\tau_{\rm br} \sim nv\sigma_{\rm br}, \tag{9}$$

where n is the gas density and v is the particle velocity. The value of $\tau_{\rm br}$ is of the same order for the electrons and protons. The point is that the velocities of the electron with the energy $\sim E_x$ and of the proton with the energy $\sim(M/m)E_x$ are equal. For the same reason the rates of ionization loss are also of the same order for these particles

$$\left(\frac{{\rm d}E}{{\rm d}t}\right)_{\rm i} = -\frac{2\pi ne^4}{mv} \ln \Lambda_n, \tag{10}$$

where $\ln \Lambda_n$ is a logarithmic function weakly dependent on the particle energy. But their lifetimes due to ionization losses

$$\tau_{\rm i} \sim \frac{E_{\rm e,p}}{({\rm d}E/{\rm d}t)_{\rm i}} \tag{11}$$

differ from each other by a factor (m/M). It follows from Eq. (6) that protons with energy $(M/m)E_x$ produce many more photons with energy E_x than electrons with energy E_x. Then for the same flux Q_x we have

$$\frac{Q_{\rm p}}{Q_{\rm e}} \sim \frac{m}{M}. \tag{12}$$

However, if we compare their energy outputs

$$F \sim E \cdot Q \ ({\rm erg\ s^{-1}}) \tag{13}$$

we find

$$\frac{F_{\rm p}}{F_{\rm e}} = \frac{Q_{\rm p}E_{\rm p}}{Q_{\rm e}E_{\rm e}} = \frac{(m/M)Q_{\rm e}(M/m)E_x}{Q_{\rm e}E_x} = 1. \tag{14}$$

This means that the same energy flux in protons or electrons is necessary to produce a flux of X-ray photons Q_x.

As follows from Eq. (8) the proton and electron bremsstrahlung fluxes are equal if the densities of emitting protons and electrons are equal

$$N_{\rm p}\left(\frac{M}{m}E_x\right) \sim N_{\rm e}(E_x), \tag{15}$$

since the cross-sections and velocities are the same for the electrons and protons.

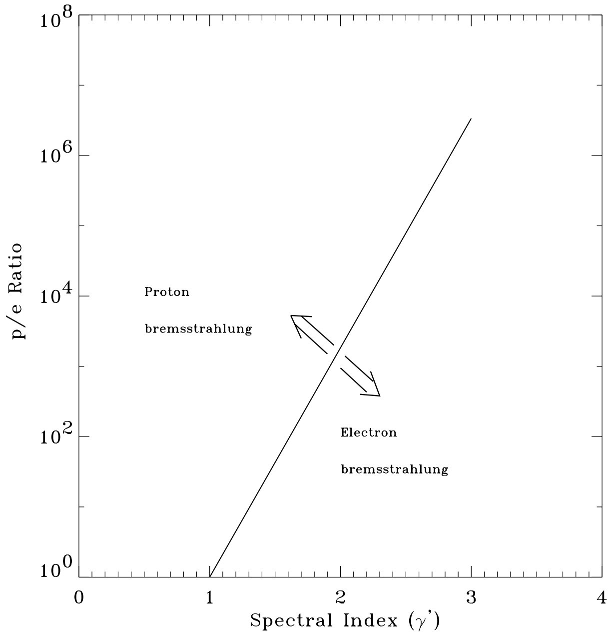

Fig. 2. The ranges of spectral parameters for predominantly proton or electron bremsstrahlung emission.

For a power-law differential spectrum of particles $N = K'E^{-\gamma'}$ the bremsstrahlung flux produced by the protons equals that produced by the electrons if

$$K'_{\rm p} \int_{m/ME_x}^{E^{\rm p}_{\rm max}} E_{\rm p}^{-\gamma'} nv \frac{{\rm d}\sigma_{\rm br}(E_{\rm p}, E_x)}{{\rm d}E_x} {\rm d}E_{\rm p}$$

$$= K'_{\rm e} \int_{E_x}^{E^{\rm e}_{\rm max}} E_{\rm e}^{-\gamma'} nv \frac{{\rm d}\sigma_{\rm br}(E_{\rm e}, E_x)}{{\rm d}E_x} {\rm d}E_{\rm e}. \tag{16}$$

It is easy to show that this condition for $\gamma' \geq 1$ reduces to

$$\frac{K'_{\rm p}}{K'_{\rm e}} \left(\frac{m}{M}\right)^{\gamma'-1} = 1 \tag{17}$$

on the assumption that the spectral index of electrons and protons is γ'.

If this ratio is less than unity then the photon flux is mainly produced by electrons, and otherwise by protons. The ratio $K'_{\rm p}/K'_{\rm e}$ (which is the proton to electron ratio at the same energy) determined from Eq. (17) is shown in Fig. 2 as a function of the spectral index γ'.

4. Processes of particle acceleration in the galactic ridge

Below we summarize the characteristics of the hard X-ray spectrum which are essential for our analysis of the acceleration process in the Galactic disk (see Yamasaki et al. 1997; Valinia & Marshall 1998; Valinia et al. 2000):

- Features of the diffuse emission in the hard X-ray band suggest a diffuse and nonthermal origin;

- The large scale association of the hard X-ray emission with the thermal X-rays implies that these two components are linked. This leads to the idea that thermal particles in the hot plasma are accelerated to produce the nonthermal particles responsible for the hard X-ray emission;
- The X-ray flux is produced in the region where the particles are freshly accelerated;
- The efficiency of the process emitting the hard X-rays drops above 40 keV;
- The regions of particle acceleration are supposed to be regions of very hot plasma with parameters: density $n \simeq 8 \times 10^{-2}$ cm^{-3} and the temperature $T \simeq$ 2.6 keV. The filling factor of this plasma is taken to be $\xi \simeq 10^{-3}$.

We see that the data definitely point to acceleration operating in the Galactic ridge with the emitting particles being accelerated from the hot thermal pool. Here we return to the old idea of Fermi on CR acceleration in the interstellar medium. In the current theory of cosmic-ray origin this mechanism of interstellar acceleration (or reacceleration) is considered as an auxiliary process only slightly changing the spectrum and chemical composition of relativistic CRs emitted by SNR (see Berezinskii et al. 1990). It may follow from the X-ray data that the processes of interstellar acceleration play instead the main role in the production of the subrelativistic CRs in the inner Galaxy.

The main process of charged particle acceleration in cosmic plasmas is in most cases collisions with magnetic field fluctuations, which leads to slow stochastic energy gain. If this magnetic turbulence is "weak", i.e. the amplitude of magnetic field fluctuations δH is much less than the strength of the large scale magnetic field H_0, $\delta H \ll H_0$, then the interaction between the particles and the fluctuations has a resonance character. This type of interaction takes place in the interstellar medium. The acceleration is more effective for the case of strong magnetohydrodynamic turbulence ($\delta H \sim H_0$). This acceleration is realized e.g. in low ionized turbulent media (see Dogiel et al. 1987) or in extended regions of hot plasma (OB associations) filled with numerous but rather weak shock waves, resulting from SN explosions there (see Bykov & Toptygin 1993). The stochastic acceleration is described in this case as momentum diffusion with the diffusion coefficient $\alpha(p)$

$$\alpha(p) = \alpha_0 p^2, \tag{18}$$

where the value α_0^{-1} is the characteristic time of the stochastic acceleration. The production spectrum of the accelerated particles is very hard and it has the form in subrelativistic and relativistic energy ranges

$$Q(E) \propto E^{-1}. \tag{19}$$

This circumstance allows in principle to distinguish between stochastic acceleration (18) and acceleration by supernova shocks which produce softer spectra.

The stochastic acceleration (18) will be analysed below.

5. Number of accelerated particles

In order to estimate how many subrelativistic particles can be produced by this mechanism we solve the equation describing the spectrum in the thermal and nonthermal energy ranges.

The equilibrium (Maxwellian) spectrum of background charged particles is produced by Coulomb collisions. In an ionized plasma which consists of protons and electrons the energy loss of a test particle with velocity v, charge Z and atomic number A due to these collisions has the form (see, e.g., Butler & Buckingham 1962; Sivukhin 1964)

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{4\pi Z^2 e^4 n \ln\Lambda}{AMv} \times \left(G(v/v_T^{\mathrm{p}}) + (M/m)G(v/v_T^{\mathrm{e}})\right), \tag{20}$$

where

$$G(x) = \frac{2}{\sqrt{\pi}}\left[\int_0^x \exp(-z^2)\mathrm{d}z - \left(1+\frac{\hat{m}}{M}\right)x\exp(-x^2)\right], \tag{21}$$

$\hat{m}$ is the rest mass of a background charged particle, v_T^{p} and v_T^{e} are the thermal velocities at the temperature kT of the background protons and electrons

$$v_T^{\mathrm{p}} = \sqrt{\frac{2kT}{M}} \quad \text{and} \quad v_T^{\mathrm{e}} = \sqrt{\frac{2kT}{m}}, \tag{22}$$

and

$$\Lambda = \frac{kTd}{e^2}\cdot \tag{23}$$

Here d is the Debye radius

$$d = \sqrt{\frac{kT}{8\pi n e^2}}\cdot \tag{24}$$

From Eq. (20) it is clear that the energy loss rate of ions has at least two maxima at velocities $v \sim v_T^{\mathrm{p}}$ and $v \sim v_T^{\mathrm{e}}$.

The equation for stochastic acceleration forming the spectrum of nonthermal particles and Coulomb collisions forming an equilibrium Maxwellian spectrum of background particles in the energy range above kT has the form

$$\frac{\partial f}{\partial \tau} - \frac{1}{u^2}\frac{\partial}{\partial u}\left(A(u)\frac{\partial f}{\partial u} + B(u)f\right) = 0\,. \tag{25}$$

Here f is the particle distribution function, τ and u are the dimensionless time and the proton velocity:

$$\tau = \nu_0 t \quad \text{and} \quad u = \frac{v}{\sqrt{kT/\hat{m}}}\,, \tag{26}$$

ν_0 is the collisional frequency of background particles at $E = kT$ and $\hat{m}$ is the rest mass of the accelerated particles. The frequency ν_0 is

$$\nu_0 = \frac{4\pi n Z^2 e^4}{(kT)^{3/2}\hat{m}^{1/2}}\ln\left(\frac{kTd}{e^2}\right)\cdot \tag{27}$$

To estimate the number of accelerated particles we must analyze the range of velocities $u > 1$ where the functions $A(u)$ and $B(u)$ are

$$A(u) = \frac{1}{u} + \frac{1}{u}\frac{M}{m}G\left(u\sqrt{\frac{m}{2M}}\right) + \alpha_0^{\rm p}(u)u^4 \quad (28)$$

and

$$B(u) = 1 + \frac{M}{m}G\left(u\sqrt{\frac{m}{2M}}\right) \quad (29)$$

for protons and

$$A(u) = \frac{1}{u} + \alpha_0^{\rm e}(u)u^4 \quad (30)$$

and

$$B(u) = 1 \quad (31)$$

for electrons.

The nondimensional momentum diffusion coefficient $\alpha(u)$ describes processes of stochastic acceleration which in many cases has the form (see, e.g., Toptygin 1985)

$$\alpha(u) = \alpha_0 u^2, \quad (32)$$

and the other terms describe Coulomb collisions with the background protons and electrons. For the same acceleration frequency α_0' the values of the nondimensional α_0 are different for electrons and protons: $\alpha_0^{\rm e,p} = \alpha_0'/\nu_0^{\rm e,p}$.

This acceleration violates the equilibrium state of the particle distribution determined by Coulomb collisions since particles with energies above the injection energy (where acceleration is significant) continuously increase their energy. Collisions tend to compensate this particle loss causing the energy of thermal particles to increase from the main equilibrium value to the injection energy and as a result a flux of particles "running away" into the high energy range occurs in the spectrum even at energies far below the injection energy. The value of the total run-away flux (for protons and electrons) has the form (see Gurevich 1960)

$$\left(\frac{{\rm d}\bar{N}}{{\rm d}t}\right)_{\rm p}^{\rm r} \simeq \sqrt{\frac{2}{\pi}}n\nu_0^{\rm p}(1+M/m) \times \exp\left(-\int_0^\infty \frac{u{\rm d}u(1+(M/m)G(u/\sqrt{2M/m}))}{1+(M/m)G(u/\sqrt{2M/m})+\alpha_0^{\rm p}u^5}\right), \quad (33)$$

$$\left(\frac{{\rm d}\bar{N}}{{\rm d}t}\right)_{\rm e}^{\rm r} \simeq \sqrt{\frac{2}{\pi}}n\nu_0^{\rm e}\exp\left(-\int_0^\infty \frac{u{\rm d}u}{1+\alpha_0^{\rm e}u^5}\right). \quad (34)$$

The ratio of the proton and electron run-away fluxes for different values of the nondimensional parameter $\alpha_0^{\rm e} = \alpha_0'/\nu_0^{\rm e}$ are shown in Fig. 3.

From Fig. 3 we see that protons are accelerated much more effectively than electrons. This means that in the case of interstellar acceleration it is easier to produce non-thermal protons than electrons.

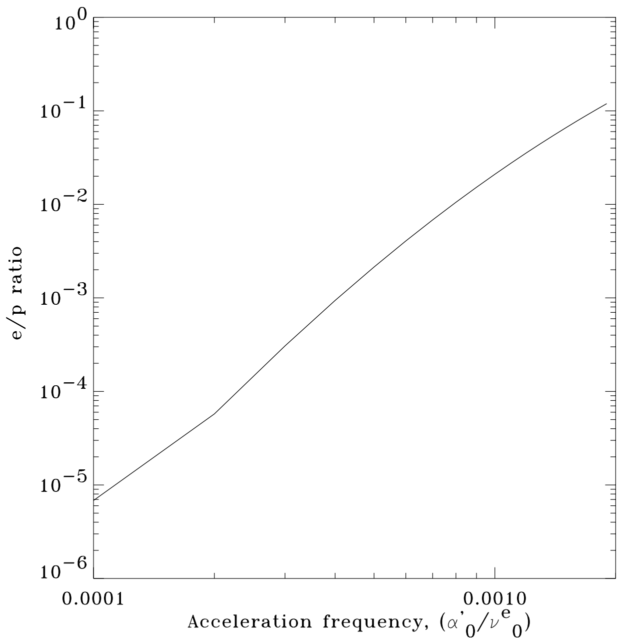

Fig. 3. The ratio of the run-away fluxes (electrons to protons). The dimensionless acceleration frequency α_0 is normalized to the collision frequency $\nu_{\rm e}^0$.

As follows from the analysis of the kinetic Eq. (25) the spectrum of accelerated particles is hard and has the form E^{-1}. The production rate Q of particles can be determined from the value of their run-away flux as

$$Q(E) = K \cdot E^{-1}\theta(E_{\max} - E), \quad (35)$$

where Eqs. (33) and (34) determine the constants K for protons and electrons, and $\theta(x)$ is the Heaviside function (step-function). The energy $E_{\max}$ determines a cutoff in the spectrum where the efficiency of acceleration drops.

For stochastic acceleration $E_{\max}$ can be derived from the spectrum of electromagnetic turbulence (see e.g. Dogiel et al. 1987). However, since we do not specify the mechanism of acceleration its value is uncertain though e.g. for the case of supersonic turbulence in OB associations the maximum energy of accelerated protons was estimated to be of the order of 100 MeV (see Bykov & Bloemen 1997). The maximum energy of electrons can be smaller than hundreds of keV (see Sect. 10).

In general the value of $E_{\max}$ is determined by the efficiency of particle acceleration and by processes which prevent particle acceleration above a certain energy (e.g. particle escape from the acceleration region or the feedback reaction of accelerated particles on the efficiency of acceleration). As we mentioned already we do not know the details of the acceleration processes in the galactic disk, and therefore we are unable to estimate the value of $E_{\max}$ in this way.

Fortunately, in our case the value of $E_{\max}$ can be directly derived from the observed X-ray spectrum. To reproduce the X-ray spectrum (5) we must assume that the maximum energy does not exceed significantly the value of 100 keV for the accelerated electrons or 100 MeV for the accelerated protons, which is close to the value from theoretical estimates for the interstellar acceleration of nuclei (see, e.g., Bloemen & Bykov 1997).

6. Chemical composition of the accelerated particles

The interstellar stochastic acceleration is described as momentum diffusion with the diffusion coefficient

$$\alpha(p) = \alpha_0' p^2. \tag{36}$$

Then the average rate of acceleration can be determined as

$$\frac{\mathrm{d}E}{\mathrm{d}t} \simeq \alpha_0' E. \tag{37}$$

It is clear that the acceleration generates a particle spectrum at energies higher than the injection energy which is determined from the equality between the ionization losses and the acceleration

$$E_{\rm inj} \simeq Z^{4/3} A^{1/3} \left(\frac{4\pi e^4 n \ln\Lambda \sqrt{M_{\rm p}}}{\sqrt{\pi} m \alpha_0'} \right)^{2/3}, \tag{38}$$

where A is the particle atomic number. We see that the flux of the accelerated particles is a function of the particle charge Z. Therefore it would not be surprising if the chemical composition of the accelerated particles differs from the chemical composition of the background plasma.

The flux of ions escaping from the thermal part of the spectrum into the acceleration region can be represented as (Gurevich 1960)

$$\begin{aligned} \frac{\mathrm{d}f}{\mathrm{d}t} = & \ \eta(Z)\sqrt{\frac{2}{\pi}} n \frac{Z^2}{A^{0.5}} \nu_0^{\rm p} \frac{M}{m} \\ & \times \exp\left(-\frac{Z^2 q}{2\alpha_0^{\rm p} A^{0.5}} \sqrt{\frac{m}{M}} \right), \end{aligned} \tag{39}$$

where q is of the order of unity and $\eta(Z)$ is the abundance in the background gas. From this equation we see that the abundance of ions with $Z > 1$ in the flux of accelerated particles is strongly suppressed compared to the abundance of elements in the background plasma and therefore the abundances of the background gas and that of the accelerated nuclei are quite different.

The chemical composition of subrelativistic nuclei accelerated from the thermal pool is shown in Fig. 4. In the figure we show the ratio of the nuclear abundance in the flux of the accelerated particles $\eta_{\rm CR}$ to the abundance in the background gas $\eta_{\rm b}$. The abundance of element in the background gas is taken as unity for all elements (straight dashed line). The chemical composition of the accelerated particles was calculated for acceleration frequencies $\alpha_0'/\nu_0^{\rm p} = 10^{-2}$ shown by asterisks and for $\alpha_0'/\nu_0^{\rm p} = 8.85 \times 10^{-4}$ shown by triangles. For the calculations we used Eq. (33) which gives a more accurate result than the approximation (39).

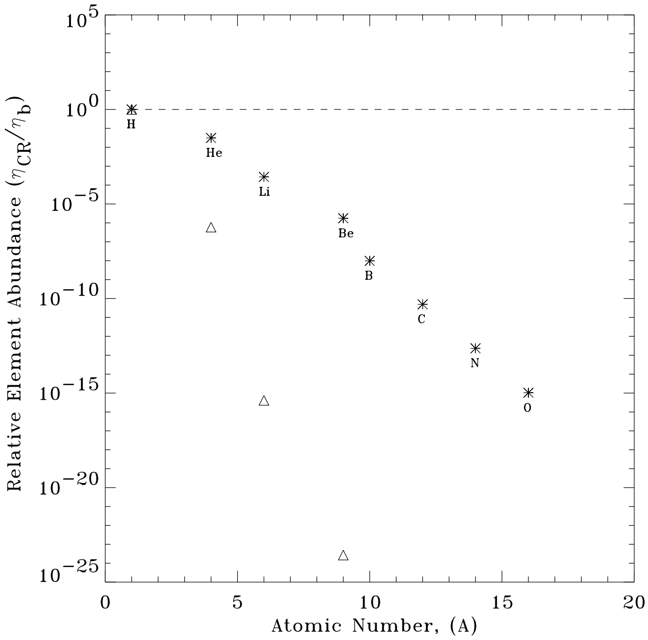

Fig. 4. The relative abundance of elements in the background gas (straight dashed line) and in the flux of particles ($\eta_{\rm CR}/\eta_{\rm b}$) accelerated from the thermal pool (asterisks), calculated for $\alpha_0'/\nu_0^{\rm p} = 10^{-2}$. The result of calculations for the acceleration parameter $\alpha_0'/\nu_o^{\rm p} = 8.85 \times 10^{-4}$ is shown by triangles.

7. Spatial distribution of the subrelativistic particles in the galaxy

The transformation of the injection spectrum (35) in the interstellar medium is due to processes of energy losses and spatial propagation. The cosmic ray propagation is described as diffusion in the interstellar medium with the effective diffusion coefficient D and the convection velocity u. The propagation equation in the general form is

$$\nabla(uN - D\nabla N) - \frac{\partial}{\partial E}\left(\frac{\mathrm{d}E}{\mathrm{d}t} N \right) = Q(r, E), \tag{40}$$

where $\mathrm{d}E/\mathrm{d}t$ describes the rate of energy losses.

Below we obtain rather simple solutions of the one dimensional propagation equation for subrelativistic protons and electrons. The particle production for the case of the interstellar acceleration is described by Eq. (35). The spectrum of particles depends strongly on the particle mean free path λ determined by the processes of diffusion and energy losses

$$\lambda \sim \sqrt{D\tau_{\rm l}}, \tag{41}$$

where $\tau_{\rm l}$ is the characteristic life-time of the particles determined by the energy losses. There are three other spatial scales which characterize the distribution of the CR sources $z_{\rm s}$, the gas $z_{\rm g}$ and the volume of the particle propagation (halo) $z_{\rm h}$.

If $\lambda < z_{\rm s}$ the propagation is unimportant and the kinetic equation has the form

$$\frac{\mathrm{d}}{\mathrm{d}E}\left(\frac{\mathrm{d}E}{\mathrm{d}t} N \right) = K E^{-\gamma}, \tag{42}$$

where the right hand side of the equation describes the injection spectrum and $\mathrm{d}E/\mathrm{d}t \simeq -a/E^{0.5}$ is the rate of ionization losses. The solution of this equation is

$$N = \frac{KE^{-(\gamma-3/2)}}{\mid \gamma - 3/2 \mid a}\cdot \tag{43}$$

If $z_{\mathrm{z}} < \lambda < z_{\mathrm{g}}$ particles escape from the acceleration region and the equation has the form

$$D\frac{\partial^2}{\partial z^2}N + \frac{\partial}{\partial E}\left(\frac{\mathrm{d}E}{\mathrm{d}t}N\right) = -KE^{-\gamma}z_{\mathrm{s}}\delta(z) \tag{44}$$

and the solution is

$$N(E) = \frac{Kz_{\mathrm{s}}}{\mid \mathrm{d}E/\mathrm{d}t \mid}\int\limits_0^\infty \mathrm{d}E_0 \exp\left(-\frac{z^2}{4D\tau}\right)\frac{E_0^{-\gamma}}{\sqrt{4D\tau}} \tag{45}$$

where

$$\tau(E, E_0) = \int\limits_{E_0}^{E} \frac{\mathrm{d}E'}{\mathrm{d}E'/\mathrm{d}t}\cdot \tag{46}$$

If the particles lose their energy in the gaseous disk ($\lambda < z_{\mathrm{g}}$) then we obtain

$$N \sim K\sqrt{\frac{at_{\mathrm{d}}}{4\pi}}E^{-(\gamma-\frac{3}{4})} \tag{47}$$

and if particles leave the gaseous disk, then the energy losses are unimportant and the solution is

$$N \simeq \frac{KE^{-\gamma}z_{\mathrm{h}}^2}{D}\left(1 - \frac{z}{z_{\mathrm{h}}}\right)\cdot \tag{48}$$

We see that the effect of ionization energy losses is a flattening of the accelerated spectrum. Therefore we expect that the spectral index γ' of particles in the interstellar medium ($N \propto E^{-\gamma'}$) is equal to or less than the injection spectral index γ ($Q \propto E^{-\gamma}$). The injection index γ of subrelativistic particles accelerated by shock waves is 1.5 and that for the stochastic acceleration by chaotic electromagnetic turbulence is 1. Therefore we expect that the spectral index of fast particles in the interstellar medium is in the range $-0.5 \leq \gamma' \leq 1.5$.

8. Bremsstrahlung X-ray emission from the ridge

From Sects. 4 and 6 we concluded that the spectrum of the X-ray emitting particles is a power-law with an exponential cut-off

$$N(E) \simeq K(\gamma')E^{-\gamma'}\exp\left(-\frac{E}{E_{\max}(\gamma')}\right)\cdot \tag{49}$$

Then we can formally derive the values of $K(\gamma')$ and $E_{\max}$ for different values of γ' from the observed intensity of the hard X-ray emission using the equation for bremsstrahlung radiation (8).

Below we denote as Spectrum I the spectrum of the emitting particles which produce the hard X-ray emission in the range 10–200 keV shown in Fig. 5 by the solid line. The spectrum of the particles which produce the emission in the GINGA-RXTE range only (shown by the dashed line in Fig. 5) will be denoted as Spectrum II.

Table 1. Parameters of the emitting spectrum of protons (p) consistent with for Spectrum I and Spectrum II. For electrons the position of the break can be obtained from $E^{\mathrm{e}}_{\max} = E_{\max}(m/M)$.

γ'	1	0.5	0.1	–0.5
$E^{\mathrm{I}}_{\max}$ MeV	470	300	250	150
$E^{\mathrm{II}}_{\max}$ MeV	65	55	45	35

We took the gas column density in the direction of the Galactic ridge as $\sim 10^{22}$ cm^{-2} assuming that the accelerated particles fill the whole volume of the ridge.

The spectra of hard X-rays from GINGA presented in Yamasaki et al. (1997) and from RXTE by Valinia & Marshall (1998) were observed for different regions of the Galactic ridge and therefore their intensities differ by a factor of 3–5. Hence we derived the spectrum separately for these observations. The results of the measurements are presented in Figs. 5 and 6. The densities of the particles derived from the RXTE and GINGA data differ also by a factor 3–5. To present the results in the same units we took the total area of the central radian observed by GINGA, namely 456 grad^2 (the average width of the ridge is $\sim 8°$ (Valinia, private communication). Below we base our analysis on the RXTE data since they represent the average X-ray spectrum in the Galactic ridge. In both cases we took the component below 10 keV to be due to the thermal bremsstrahlung at a temperature of 2.6 keV.

The results of our calculations for the RXTE data are shown in Fig. 5. We obtained almost the same X-ray spectrum for different γ' and $E_{\max}(\gamma')$ by adjusting these parameters.

As an example we show in Table 1 for Spectrum I and Spectrum II how the break position $E_{\max}$ in the spectrum of protons changes with the value of the spectral index γ'.

Spectra for all values of $\gamma' \leq 1$ nicely describe the RXTE data. It is clear that steeper electron spectra are unable to reproduce the flat RXTE spectrum. The result of calculations for $\gamma' = 2$ are shown in the figure. From Eq. (8) the X-ray spectrum is then proportional to $E_x^{-2.5}$ which is much steeper than the observed spectrum at energies below 30 keV.

Similar calculations based on the GINGA data are shown in Fig. 6. Qualitatively the conclusion is the same – the ridge emission is produced by a flat spectrum of emitting particles whose spectral index is $\gamma' \leq 1$.

In principle we can extend our calculations to the region of the OSSE data up to 200 keV in order to reproduce the total hard X-ray flux from the ridge by the bremsstrahlung emission of the accelerated particles.

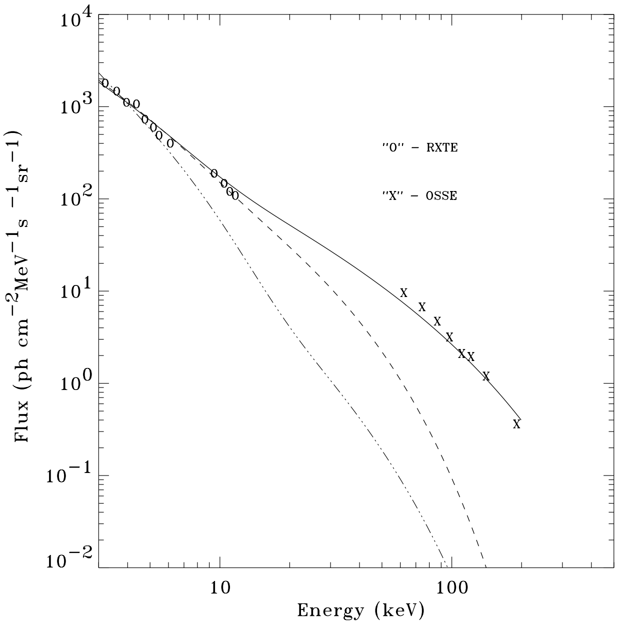

Fig. 5. The flux of hard X-ray emission measured by the RXTE and OSSE telescopes. The spectrum of bremsstrahlung radiation (generated by protons or electrons) reproducing the RXTE-OSSE Spectrum I (solid line) and that for the RXTE Spectrum II only (dashed line). The spectrum for $\gamma' = 2$ is shown by the dashed-dotted line. The parameters $E_{\max}(\gamma')$ and $K(\gamma')$ were derived for each value of the spectral index γ to satisfy the observational data.

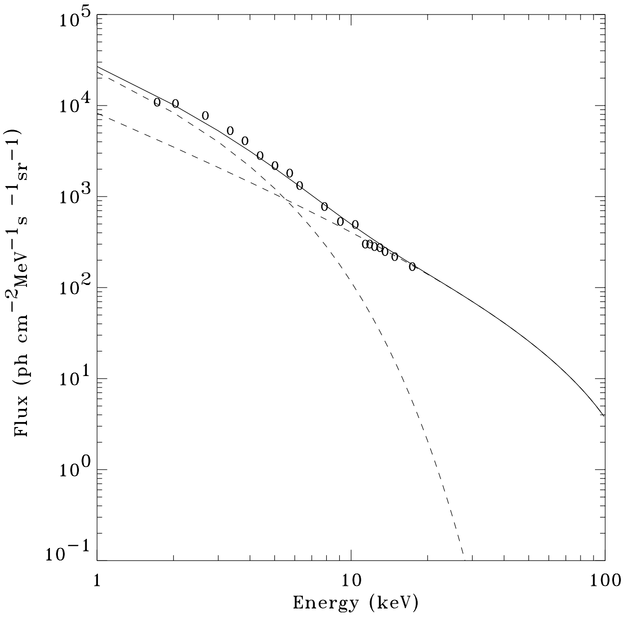

Fig. 6. The flux of hard X-ray emission measured by the GINGA telescope for the central Galactic radian. The bremsstrahlung radiation was computed for a spectral index $\gamma' = 0.1$. Spectra of the thermal and nonthermal emission are also shown in the figure.

However as we remarked in the Introduction the origin of this part of the ridge spectrum is unclear. Results of the calculations are shown in Fig. 5 by the solid line. In the range between 200 to 500 keV part of the flux is from three-photon positronium continuum emission. Therefore, OSSE data in this energy range are excluded in Fig. 5.

The important conclusion following from these calculations is: the data can be reproduced by bremsstrahlung emission of the accelerated particles only if $\gamma' \leq 1$. The cut-off energy $E_{\max}$ for Spectrum I is of the order of 150–500 MeV for protons and 80–270 keV for electrons. The cut-off energy for Spectrum II equals 35–50 MeV for protons and 20–30 keV for electrons.

Below we consider separately the details of protons and electrons as the origin of the hard X-rays.

9. Proton bremsstrahlung origin of the ridge X-rays

9.1. Parameters of the proton spectrum

First of all we estimate from the ridge X-ray spectrum the total density of protons $\bar{N}$

$$\bar{N} = \int^{\infty} N(E)\mathrm{d}E, \tag{50}$$

their energy density w

$$w = \int^{\infty} EN(E)\mathrm{d}E, \tag{51}$$

the total energy power F (if the particle loss from the ridge is due to the ionization losses (10))

$$F = V\int^{\infty} N(E)\frac{\mathrm{d}E}{\mathrm{d}t}\mathrm{d}E, \tag{52}$$

where V is the volume of the emitting region of 10^{67} cm^3 (Valinia & Marshal 1998), and the total (integrated over energies) particle flux $\mathrm{d}\bar{N}/\mathrm{d}t$ due to the losses which has to be compensated by the acceleration

$$\left(\frac{\mathrm{d}\bar{N}}{\mathrm{d}t}\right)_{\mathrm{i}} \sim \int^{\infty} \frac{N(E)}{\tau_{\mathrm{i}}}\mathrm{d}E, \tag{53}$$

with τ_{i} from Eq. (11).

The results of the calculations for the emitting protons on the assumption that they fill the whole Galactic disk (filling factor $\xi = 1$) are presented in Table 2. These parameters calculated for Spectrum I and Spectrum II do not differ greatly.

We see that the energy density of the subrelativistic protons must be very high in order to reproduce the X-ray data. In Fig. 7 we present the expected Spectrum I (solid line) and Spectrum II (dashed line) for the subrelativistic protons together with the spectrum of protons at Earth.

The equation for α_0 can be derived from the balance between the run-away flux of the accelerated particles and

Table 2. Parameters of the accelerated protons (p) and electrons (e).

	$\bar{N}$ (cm^{-3})	w ($\mathrm{eV\ cm}^{-3}$)	$\mathrm{d}\bar{N}/\mathrm{d}t$ ($\mathrm{cm}^{-3}\mathrm{s}^{-1}$)	α_0' (s^{-1})	F ($\mathrm{erg\ s}^{-1}$)
p	2×10^{-6}	250–400	$\sim10^{-21}$	7×10^{-15}	$\sim10^{42}$
e	2×10^{-6}	0.2	$\sim10^{-18}$	3×10^{-13}	$\sim10^{42}$

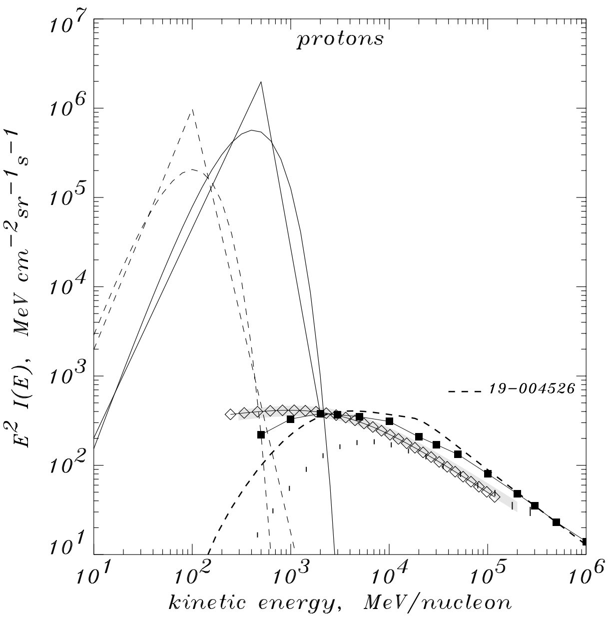

Fig. 7. The function $E^2 \cdot I(E)$ for the observed relativistic and derived subrelativistic spectra of the interstellar protons (solid line – Spectrum I; thin dashed line – Spectrum II), vertical bars – IMAX direct measured spectrum, thick dashed line the proton spectrum derived from the propagation model, connected squares and diamonds, and dashed area – different variants of the proton demodulated spectrum (see Strong et al. 2000 and references therein). We show also in the figure (triangles) the approximations to Spectrum I and Spectrum II which were used for estimates of the π° gamma-ray flux produced by the accelerated protons.

the nonthermal particle losses due to ionization. This balance fixes the density of the accelerated particles in the disk. The total production rate of the accelerated particles is determined by the momentum diffusion with the coefficient α_0. Therefore the equation for α_0 (which follows from Eq. (40)) has the form

$$\left(\frac{\mathrm{d}\bar{N}}{\mathrm{d}t}\right)_{\mathrm{i}} \simeq \left(\frac{\mathrm{d}\bar{N}}{\mathrm{d}t}\right)^{\mathrm{r}}. \tag{54}$$

Here the LHS can be estimated from Eq. (53) where the density of the emitting particles is derived from the observed flux of hard X-rays. The RHS of this equation is determined by Eqs. (33) and (34) for protons and electrons respectively, and clearly it is a function of the parameter α_0 only.

The flux of run-away particles $\left(\mathrm{d}\bar{N}/\mathrm{d}t\right)^{\mathrm{r}}$ is formed by collisions of thermal particles whose distribution is not sensitive to the nonthermal part of the spectrum. Therefore, as one can see from Eqs. (33) and (34) this run-away flux is a function of the parameter α_0 only.

The LHS of Eq. (54) is completely determined by the characteristics of the observed spectrum of hard X-ray emission from the Galactic Ridge. As was shown in Sect. 8 the maximum energy of emitting particles chosen to reproduce the spectrum of X-rays can vary over rather wide limits (depending on assumption of the contribution from unresolved sources). However, these variations only weakly (logarithmically) change the derived value of α_0. On the other hand, the density of accelerated particles strongly (exponentially) depends on α_0 and even small variations of α_0 change this density significantly.

From Eq. (54) we find that the proton acceleration frequency equals $\alpha_0'/\nu_0^{\mathrm{p}} \simeq 1.3\times10^{-3}$ almost independent of the γ' value.

The frequency of proton collisions ν_0^{p} at energy $E = kT$ (see Eq. (27)) in the acceleration regions is:

$$\nu_0^{\mathrm{p}} \simeq 5.3\times10^{-12}\ \mathrm{s}^{-1}. \tag{55}$$

Here we took $n \simeq 8\times10^{-2}\ \mathrm{cm}^{-3}$ and $T \simeq 2.6$ keV for regions of the interstellar medium heated by SNs (see Yamasaki et al. 1997).

Then the characteristic acceleration frequency is

$$\alpha_0' \sim 7.1\times10^{-15}\ \mathrm{s}^{-1} \tag{56}$$

for protons.

9.2. Gamma-ray line emission from the Galactic ridge

The chemical composition of the accelerated ions is important for estimates of gamma-ray line emission from the Galactic ridge which is expected in the case of a nuclear bremsstrahlung origin of the X-ray emission. The most prominent 4.4 MeV ^{12}C and 6.1 MeV ^{16}O line flux from the Galactic ridge was estimated by Pohl (1998) and Valinia et al. (2000b) for hypothetical spectra of subrelativistic protons and electrons. Their conclusions were not in favor of the inverse bremsstrahlung model since the calculated line flux was much higher than the upper limits derived from the OSSE and COMPTEL observations. On the other hand they used for their estimates the observed CR chemical composition which can differ from the chemical composition of subrelativistic nuclei accelerated from the thermal pool. Hence we re-calculated the line flux from the ridge in the framework of our model.

The line flux can be estimated from

$$Q_\gamma = \int\limits_E \sigma_\gamma \eta n v N_{\mathrm{p}} \mathrm{d}E, \tag{57}$$

where η is the abundance of ^{12}C and ^{16}O in the background gas, and σ_γ is the cross-section for the line production.

For our estimates we used the solar abundances $\eta_{\mathrm{C}} \simeq 3.63\times10^{-4}$ and $\eta_{\mathrm{O}} \simeq 8.5\times10^{-4}$ as the ^{16}O and ^{12}C abundances of the background gas. The cross-sections were taken from Ramaty et al. (1979). We remind the reader

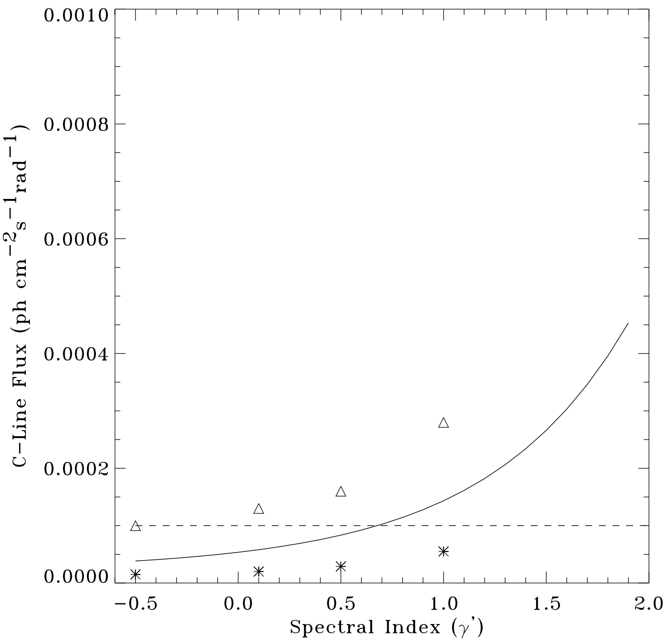

Fig. 8. The expected flux in the 4.4 MeV ^{12}C line calculated for a proton spectrum consistent with the RXTE data (solid line) based on the chemical composition of the accelerated nuclei (39). The straight dashed line shows the marginal 3 to 7 MeV flux observed with COMPTEL in the direction of the Galactic ridge. The line flux calculated for different γ' in Spectrum I is shown by asterisks and that for Spectrum II by triangles. The parameters $E_{\max}(\gamma')$ and $K(\gamma')$ were derived for each value of the spectral index γ' to satisfy the observational X-ray data.

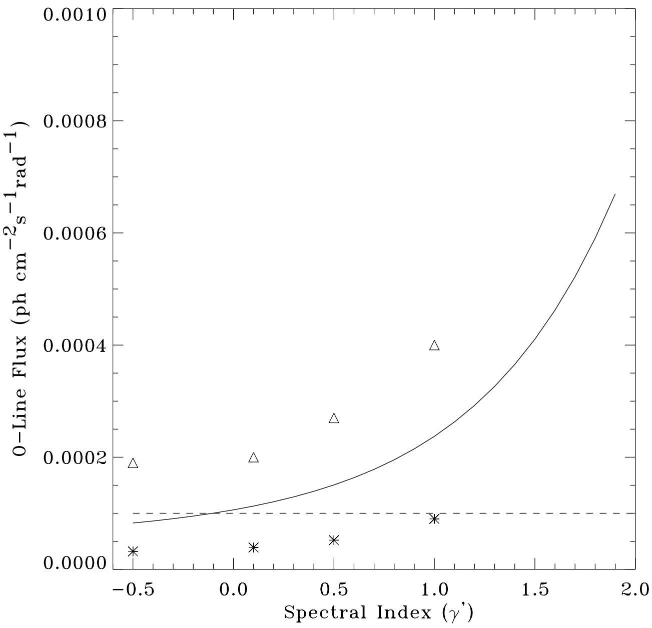

Fig. 9. The expected flux in the 6.1 MeV ^{16}O line calculated for a proton spectrum consistent with the RXTE data (solid line) based on the chemical composition of the accelerated nuclei (39). The straight dashed line shows the marginal 3 to 7 MeV flux observed with COMPTEL in the direction of the Galactic ridge. The line flux calculated for different γ' in Spectrum I is shown by asterisks and that for the Spectrum II by triangles. The parameters $E_{\max}(\gamma')$ and $K(\gamma')$ were derived for each value of the spectral index γ' to satisfy the observational X-ray data.

again that in the framework of this model the lines are produced in interactions of fast protons with background ^{12}C and ^{16}O nuclei only.

The total flux of X-ray emission produced by protons can be written in the form

$$Q_{\rm X} = \int\limits_{(M/m)E_x} \sigma_{\rm X} n v N_{\rm p} {\rm d}E, \tag{58}$$

where the cross-section $\sigma_{\rm X}$ is taken from Eq. (7). Since the X-ray and γ-ray fluxes are produced by the same subrelativistic nuclei interacting with the background gas, their ratio is independent of the gas density, and for the power-law spectrum of the nuclei (below the cut-off energy $E_{\max}$)

$$N_{\rm p} = K'(\gamma') \cdot E^{-\gamma'} \tag{59}$$

this ratio is also independent of the density of the subrelativistic cosmic rays. If we use as the normalization level the X-ray flux derived from the observations then the expected intensity of the gamma-ray line is

$$Q_\gamma = Q_{\rm X} \cdot \frac{\int\limits_{E}^{E_{\max}} \sigma_\gamma \eta v E^{-\gamma'} {\rm d}E}{\int\limits_{(M/m)E_x}^{E_{\max}} \sigma_{\rm X} v E^{-\gamma'} {\rm d}E}. \tag{60}$$

From Eq. (60) we see that the value of Q_γ is a function of the unknown spectral index γ' only.

The expected flux of the ^{12}C line from the Galactic ridge calculated based on the RXTE X-ray flux is shown in Fig. 8 and the flux of the ^{16}O line is shown in Fig. 9. From these figures we can conclude that the limits following from the estimates of the gamma-ray line emission are not very restrictive for hard spectra. We notice here that a marginal detection of a 3 to 7 MeV excess at the level $\sim 10^{-4}$ ph cm^{-2}s^{-1}rad^{-1} in the direction of the Galactic center was obtained with the COMPTEL telescope (Bloemen & Bykov 1997) which is just near the level of our estimates.

In Figs. 8 and 9 we present also the fluxes of the ^{12}C and ^{16}O line obtained for different parameters (γ', $E_{\max}(\gamma')$ and $K(\gamma')$) of the proton Spectrum I (asterisks) and Spectrum II (triangles). We see the position of the exponential cut-off is strongly constrained by the upper limit derived from the COMPTEL (and OSSE) data. In the case of rather small values of $E_{\max}$ ($\sim$30−50 MeV) the line flux generated by the protons exceeds this upper limit since in this case the protons are concentrated near the energy where the cross-section for the line production is maximum.

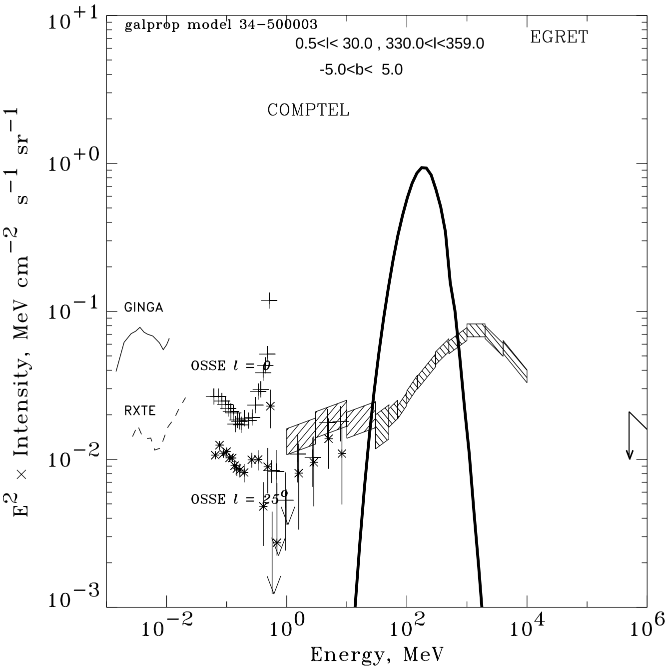

Fig. 10. The π° gamma-ray emission produced by proton Spectrum I.

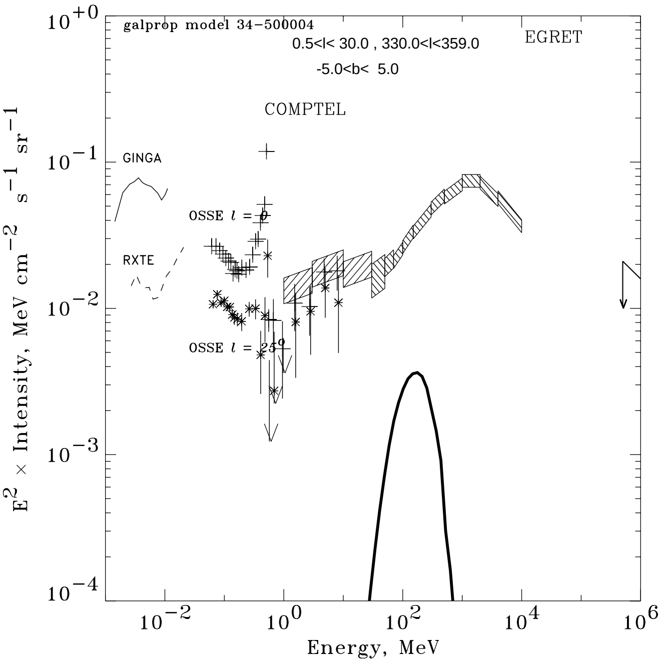

Fig. 11. The π° gamma-ray emission produced by proton Spectrum II.

9.3. The flux of π° gamma-ray emission produced by the accelerated protons

The π°-decay gamma-ray photons are generated in collisions of the accelerated protons with the background gas. The flux was calculated with the model described in Strong et al. (2000) and is shown in Fig. 10. The emission is concentrated in an narrow energy range – between 30 and 1000 MeV. The lower boundary is determined by the threshold energy of π° production and the upper boundary by the cut-off in the proton spectrum.

The gamma-ray flux generated by protons with Spectrum I is a factor 100 higher than measured. The reason is that the number of protons above the π° threshold is high (see the solid line in Fig. 7).

The gamma-ray flux produced by protons with Spectrum II (see Fig. 11) is negligible when compared with the observed ridge flux because of the rather low cut-off energy (see the dashed line in Fig. 7).

Hence we conclude that it is problematic to explain the whole nonthermal spectrum up to 200 keV by proton bremsstrahlung. However, this model successfully explains the emission up to several tens of keV. In the latter case there must be another source of hard X-ray emission at energies ∼100 keV, e.g. unresolved point-like sources. It is interesting to notice that a similar problem arises in the interpretation of the diffuse Galactic gamma-ray data at energies below 30 MeV where an excess of the emission was found which cannot be produced by bremsstrahlung of the CR electrons and it which may also be due to the emission of unresolved sources (Strong et al. 2000).

Thus we see that in addition to the analysis of the gamma-ray line flux observed continuum, gamma-ray flux restricts the value of $E_{\max}$ from above. Combining the analyses of the Sects. 7.2 and 7.3 we conclude that the value of $E_{\max}$ for, e.g., the spectrum $N \propto \sqrt{E}$ should lie between 35 MeV and 150 MeV in order not to exceed either the line or continuum fluxes.

In principle the whole flux of hard X-ray emission up to 200 keV can be produced by proton bremsstrahlung if the cut-off is much steeper than exponential and if the cut-off energy does not exceed the threshold energy for π° production (∼400 MeV). For an extreme spectrum of protons, $N(E) \propto E^{-\gamma'}\theta(400\ \mathrm{MeV} - E)$ the π° flux is zero but these protons produce X-ray emission up to 200 keV (see Fig. 12). In this case we do not have problems with the line emission since it is only 2.2×10^{-5} ph cm^{-2} s^{-1}rad^{-1} for the ^{16}O line and 8×10^{-6} ph cm^{-2} s^{-1}rad^{-1} for the ^{12}C line.

10. Electron bremsstrahlung origin of the ridge X-rays

The estimates of the parameters for the emitting electrons on the assumption that they fill the whole Galactic disk (filling factor $\xi = 1$) are presented in Table 1. If we compare these values with those of the protons from Table 1 we find that the energy density of the emitting electrons is much lower than that of the protons. On the other hand, the electrons need more effective acceleration than protons because of the high rate of ionization loss.

The frequency of electron collisions ν_0^{e} at $E = kT$ is:

$$\nu_0^{\mathrm{e}} \simeq 2.3 \times 10^{-10}\ \mathrm{s}^{-1}. \tag{61}$$

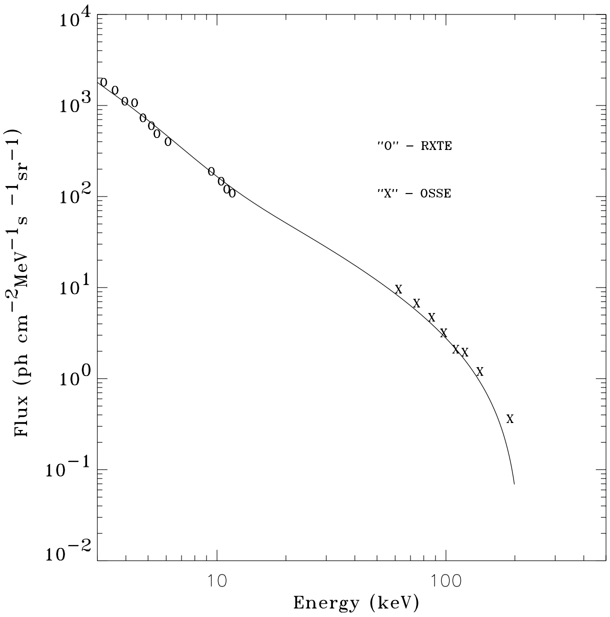

Fig. 12. The X-ray emission produced by a proton spectrum with a sharp cut-off (step-function) at 400 MeV.

Then from Eq. (54) we obtain that $\alpha_0'/\nu_0^{\rm e} \simeq 1.15 \times 10^{-3}$ or

$$\alpha_0' \sim 2.6 \times 10^{-13}\ {\rm s}^{-1} \text{ for electrons.} \tag{62}$$

It is interesting to notice that the time of in situ acceleration of electrons $(\alpha')^{-1}$ derived from the value of the ridge X-ray flux is close to obtained by Schlickeiser (1997) from the analysis of the hard X-ray flux from the ridge and electron interactions with Alfven and Whistler waves in the interstellar medium ($\sim 10^{13}$ s).

Spectrum I and Spectrum II for the emitting electrons as well as the spectra of relativistic electrons observed near Earth and the thermal spectrum (dashed-dotted-dotted line) of the hot plasma in the acceleration regions are shown in Fig. 13. If the electron bremsstrahlung interpretation of the ridge emission is correct this figure represents the total spectrum of electrons in the Galactic disk from thermal energies up to the maximum energy of electrons observed near Earth.

The question arises in the case of an electron bremsstrahlung origin of the ridge emission: why is the proton acceleration suppressed so strongly, and under what special conditions can interactions of background electrons with electromagnetic fluctuations be more effective than those of protons. Analysis of concrete acceleration processes is beyond the scope of this paper. Nevertheless, below we present speculations which may explain this effect.

The proton-electron ratio in the flux of accelerated particles was mainly analysed for the case of shock acceleration. It was shown (see e.g. Berezinskii et al. 1990) that for the same injection power the flux of protons in the relativistic energy range is much higher than that of electrons. This nicely explains the observed electron-proton ratio in the flux of the galactic CRs generated by SN shocks.

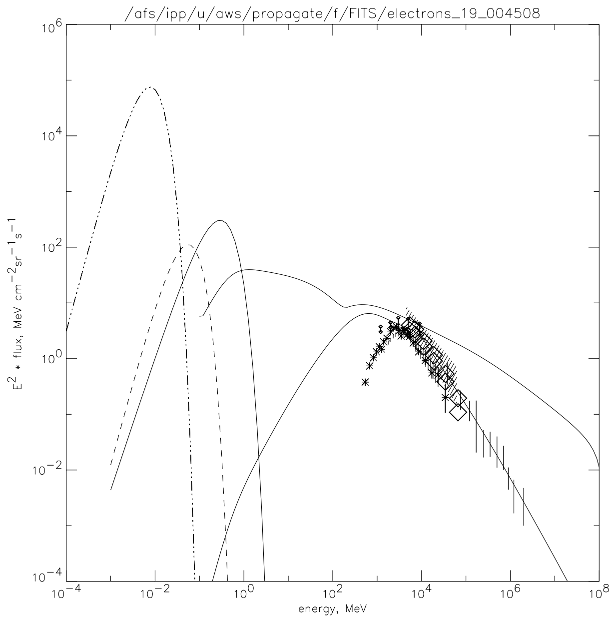

Fig. 13. The function $E^2 \cdot I(E)$ for the observed relativistic and derived subrelativistic spectra of interstellar electrons (solid line – Spectrum I, dashed line – Spectrum II), dashed-dotted-dotted line – the thermal spectrum of electrons. In the relativistic energy range measurement of the electron flux at Earth as well as the estimates of interstellar spectra derived from the radio and gamma-ray data are shown (for details see Strong et al. 2000).

The situation may be different at subrelativistic energies where the proton Larmor radius is much larger than that of electrons. We notice that the particle Larmor radius is an essential parameter which affects CR acceleration and propagation (see, e.g., Berezinskii et al. 1990). Let us consider a simple situation of particle interaction with magnetic clouds. It is clear that this interaction is effective if the particle Larmor radius is smaller than the size of the clouds. Otherwise the efficiency of particle scattering by the clouds decreases with the particle energy and as a result these particles escape almost freely from the acceleration region. As an example we can refer to the paper of Dogiel et al. (1987) where the theory of particle acceleration by neutral gas turbulence was developed. This situation may occur in the Galactic disk where the degree of ionization is not high and turbulent motions are observed (see Larson 1979).

Dogiel et al. (1987) showed that stochastic acceleration effectively generates energetic particles whose Larmor radius is less than the characteristic correlation length of the magnetic turbulence determined by dissipative processes. If the particle energy reaches a value where the Larmor radius is of the order of the correlation length any acceleration is stopped since the scattering by the magnetic fluctuations is unable to keep the particles in the acceleration region.

The energy range of accelerated particles is determined by the inequality $E > E_{\rm inj}$ where the injection energy can be estimated from Eq. (38). The injection

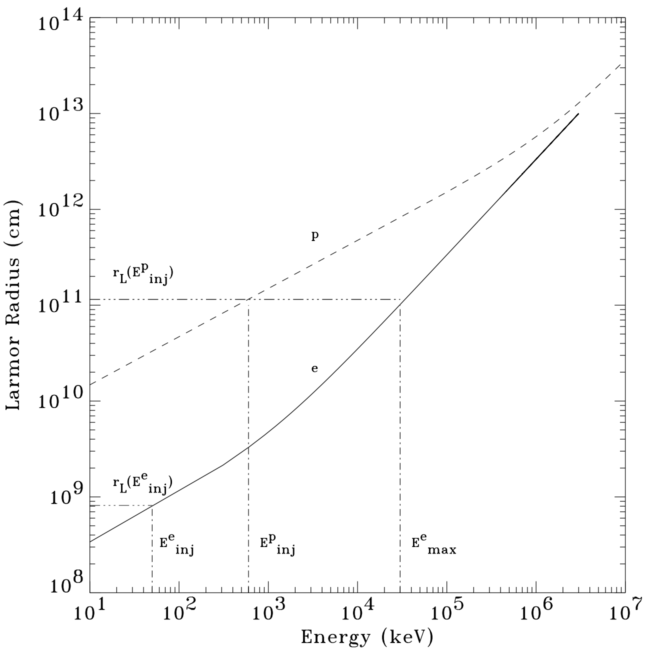

Fig. 14. Larmor radii of electrons (e) and protons (p) as a function of their energy. Vertical lines mark injection energies of electrons (at 50 keV) and protons (at 600 keV)

energy estimated from the acceleration frequency (62) equals $E^{\rm e}_{\rm inj} \sim 50$ keV for electrons and $E^{\rm p}_{\rm inj} \sim 600$ keV for protons. In Fig. 14 we present Larmor radii $r_{\rm L}$ of electrons (e) and protons (p) in the interstellar magnetic field $H \sim 3 \times 10^{-6}$ G as a function of their energy. It is clear that if the correlation length $L_{\rm cor}$ of magnetic fluctuations excited by the neutral gas turbulence lies in the interval: $r_{\rm L}(E^{\rm e}_{\rm inj}) \ll L_{\rm cor} \ll r_{\rm L}(E^{\rm p}_{\rm inj})$ then only electrons are accelerated while the proton distribution is an equilibrium Maxwellian. As we see from Fig. 14 the maximum energy of electrons in the situation of predominant electron acceleration can be as large as several tens of MeV.

These illustrative arguments present only a speculative possibility for predominant electron acceleration and careful analysis of the situation will be necessary.

11. Ionization of the interstellar medium by subrelativistic particles

Another possibility to find "traces" of particle acceleration in the interstellar medium is an analysis of the ionization state of the background gas since subrelativistic CRs effectively ionize it. This problem was discussed in Skibo et al. (1996) and Valinia & Marshall (1998). Below we estimate the rate of ionization for the spectra of protons and electrons derived from the X-ray data. The cross-section of the ionization process has the form (Spitzer & Tomasko 1968)

$$\sigma_{\rm i} \simeq 1.23 \times 10^{-20} \frac{Z^2}{\beta^2} \times \left(6.2 + \lg\left(\frac{\beta^2}{1-\beta^2}\right) - 0.43 \cdot \beta^2\right) ({\rm cm}^2). \tag{63}$$

Then the ionization rate ζ of the medium can be determined from

$$\zeta \simeq \int_E \sigma_{\rm i} v \frac{{\rm d}N}{{\rm d}E} {\rm d}E \ ({\rm s}^{-1}). \tag{64}$$

We see that the ionization rate depends on the particle velocity v and CR density N. As was mentioned before the values are the same for X-ray emitting protons and electrons and therefore $\zeta^{\rm e}_{\rm i} \simeq \zeta^{\rm p}_{\rm i}$. The value of ζ derived from the observed ridge X-ray flux for different values of the particle spectral index γ' is in the range $(8{-}30) \times 10^{-15}$ s^{-1}.

Observations of the diffuse Balmer lines give estimates for ζ in the interstellar medium which, depending on the observation direction, is between 3×10^{-15} s^{-1} and 30×10^{-15} s^{-1} (Reynolds et al. 1973); this is close to our estimates.

The source of ionization (as well as the interstellar gas heating) is an old problem (for reviews on this subject see Dalgarno & McCray 1972; and Spitzer & Jenkins 1975). The energy required to heat the interstellar medium is about $(3{-}7)\times10^{41}$ erg s^{-1} and the required energy to keep the medium ionized is of the order of $(2{-}15)\times10^{41}$ erg s^{-1}.

A central problem of these processes is the unobserved energetic radiation which maintains the heating and ionization state of the interstellar gas. A potential source which in principle could deposit significant power into the interstellar gas was considered to be either soft X-rays (Silk & Werner 1969) or a flux of low MeV cosmic rays (Hayakawa et al. 1961; Spitzer 1968). The hypothetical flux of these cosmic rays was supposed to be in the form of protons with energies 2–5 MeV (see Dalgarno & McCray 1972; Spitzer & Jenkins 1975; Nath & Biermann 1994) or in the form of subrelativistic electrons (see Sacher & Schönfelder 1984). However, at that time there were no observational data which allowed to prove any of these hypotheses. At the present time the situation is more promising.

The recent observations of the H_α-line emission from Milky Way and other galaxies are inconsistent with the pure photoionization model (Reynolds et al. 1999). In addition to photoionization another source is required, e.g., a flux of subrelativistic particles (Reynolds et al. 1999).

The observed flux of nonthermal X-rays coming from the Galactic disk suggests that there are such subrelativistic particles, although it is still unclear whether the flux consists of electrons or protons and what is the source of these particles.

12. Conclusions

From the observational data obtained with the GINGA, RXTE and ASCA telescopes it definitely follows that the flux of hard X-ray emission is nonthermal, diffuse and is probably generated by fast particles accelerated from the thermal pool. Analyses of processes which can be responsible for this emission suggest only two of them, bremsstrahlung radiation of nonthermal electrons or protons. From the kinetic equations describing particle acceleration from the thermal pool we have calculated the spectra of electrons and protons which can produce the observed X-ray flux, estimated the parameters of the acceleration process, and determined the chemical composition of the accelerated flux, which is poor in heavy elements. We have shown that the spectrum of the emitting particles should be hard in order to reproduce the observational data. These type of spectra are expected from the analysis of processes of in situ acceleration and the subsequent transformation of these spectra in the interstellar medium.

In the case of a proton bremsstrahlung origin of the ridge emission the maximum energy of the protons is of the order of 150−500 MeV if the whole range of nonthermal X-ray emission up to 200 keV is produced by the accelerated protons. An advantage of this model is the relatively "soft" acceleration conditions needed to produce the necessary proton flux. The acceleration time in this case is about 2×10^{14} s. The nuclear component with charge $Z > 1$ is strongly suppressed. Our analysis has shown that the proton bremsstrahlung model is free from the previously discussed problems of the high gamma-ray flux at MeV or at hundreds of MeV energy regions. However, the model with proton bremsstrahlung requires specific restrictions on the proton spectrum. Otherwise, the model fluxes of nuclear gamma-ray line or π° photons exceed the observational limits. The line flux produced by the accelerated protons is below the OSSE and COMPTEL upper limit if the spectrum is very hard and has a cut-off at energies of hundreds of MeV. To avoid another problem, the high flux of π° gamma-ray photons, we have to assume that the cut-off is extremely steep and its energy is just near the threshold energy for π° photon production.

The real problem of the proton bremsstrahlung model is the pressure of the accelerated protons in the disk, which as follows from Table 1 is very high, but whether or not it gives a rise to hydrodynamical motions in the Galaxy depends on the degree of coupling between the interstellar gas and the subrelativistic cosmic rays.

For the electron origin of the ridge flux we do not have the problems of the gamma-ray line and π° emission. On the other hand the electron bremsstrahlung model requires more effective acceleration of background particles with a characteristic time $\sim 10^{13}$ s. The acceleration of protons must be strongly suppressed, although we know from observational data and theoretical analyses that usually the flux of accelerated protons is larger than that of accelerated electrons, at least in the relativistic energy range[2]. We have pesented here arguments in favour of predominant electron acceleration in the subrelativistic energy range though they cannot be considered as absolutely conclusive.

In the case of an electron bremsstrahlung origin of the ridge X-ray flux a complete spectrum of electrons in the interstellar medium can be derived from the radio, X-ray and gamma-ray data. It extends from thermal keV energies up to $\sim 10^3$ GeV.

The problem of the electron bremsstrahlung model is that these electrons should produce narrow 6.4 keV iron line emission from the disk whose average flux according to the derived electron spectrum we estimate at 0.1 ph cm^{-2} s^{-1} sr^{-1}. This flux can be distinguished by the ASCA telescope and would have to be seen in the ridge spectrum as a narrow and prominent singuliarity (see Valinia et al. 2000b). However, in the Galactic ridge the 6.4 keV line was observed only from a rather small region near the galactic center in the directions of two complexes of molecular gas and its width significantly exceeds that expected for electron bremsstrahlung (Koyama et al. 1996). In other directions this 6.4 keV line has not been observed at all. Instead, the 6.6 keV iron emission is seen in the spectrum of the ridge. The width of the line in these directions is uncertain but if it is of the order of that observed for the line in the direction of the Galactic center ($\sim$100 eV) it gives a strong evidence in favour of a flux of suprathermal ions in the ridge medium (Tanaka et al. 2000). Whether or not this leads us again to the bremsstrahlung proton model, it is a goal of future analyses.

The enigma of the Galactic ridge emission is that we do not see evident sites of the particle acceleration which could supply the necessary energy flux of the order of 10^{42} erg s^{-1} needed for the production of the X-ray flux. If the other models of the Galactic ridge X-ray emission can be simply rejected by the observations, the bremsstrahlung model survives but with huge energetic problems. We can speculate only that there may be regions in the Galactic disk where the energy of hundreds or thousands of SN (as in superbubbles) or OB stars is or was accumulated and relatively recent energy fluctuations in these regions lead to this X-ray excess (in this respect see, e.g. Knödlseder 2000). Then the observed hard X-ray flux may be interpreted as an afterglow of energetic events which took place in the Galactic disk in the past and which generated a high level of turbulence there. In this case the subrelativistic protons seem preferable to electrons since they have a longer lifetime. In favour of the proton bremsstrahlung hypothesis we could mention the marginal detection of the C and O gamma-ray line emission from the Galactic ridge with the COMPTEL telescope, since in the case of the proton bremsstrahlung origin the X-ray flux should be accompanied by such gamma-ray line emission. However, this marginal detection needs confirmation.

On the observational front it should be mentioned that ESA's gamma-ray observatory INTEGRAL is due to be launched in 2002 and will provide precisely the large-scale mapping and spectral information in the energy range 20 keV-few MeV required to help resolve these issues.

In conclusion we confirm the importance of the analysis of the X-ray diffuse emission in the hard energy range.

[2] We notice, however, that for the case of shock acceleration the density of subrelativistic electrons is higher than the density of protons (Baring et al. 1999).

This analysis covers the gap between the non-thermal gamma-ray emission and the thermal soft X-ray emission and thus gives information about the connections between processes in the background plasma and the acceleration of nonthermal particles. We cannot state that our analysis has produced a definite answer on the origin of the hard X-ray emission. Nevertheless, we have formulated the general conditions under which this emission can be generated and estimated parameters of the processes which may produce the necessary fluxes of subrelativistic particles that in our opinion is a necessary step towards the solution of the problem.

Acknowledgements. The authors would like to thank Drs. M. G. Baring, H. Kaneda, A. Valinia and N. Y. Yamasaki for their comments, and Dr. R. L. Kinzer who kindly sent to us the ps-file of Fig. 1.

VAD acknowledges financial support from the Alexander von Humboldt-Stiftung which was very essential for these collaborative researches.

This work was prepared during his visit to Max-Planck-Institut für extraterrestrische Physik (Garching) and he is grateful to his colleagues from this institute for helpful and fruitful discussions.

The final version of the paper was partly done at the Institute of Space and Astronautical Science (Sagamihara, Japan). VAD thanks his colleagues from the institute and especially Prof. H. Inoue for their warm hospitality and discussions.

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