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Spectrum of subrelativistic CRs and the origin of the galactic hard X-rays

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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 ≤ 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.

If on the contrary the hard X-ray emission from the disk is emitted by subrelativistic electrons acceleration of protons is suppressed. We discuss briefly the possible origin of this effect.

This analysis of the hard X-ray emission permits to derive spectra of subrelativistic cosmic rays and thus covers the gap between the observed spectrum of relativistic cosmic rays and the thermal spectrum of background thermal particles.

1 Introduction

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. The total estimated luminosity is around $2\cdot 10^{38}$ 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.

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Observations with the RXTE telescope also show a hard X-ray excess above the thermal emission (Valinia and 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.

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 and Marshall 1998). A significant part of the emission which may be due to CR interaction with the gas and photons although there are certainly contributions from weak 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. 2000)

$$I_x \propto E_x^{-0.6}\exp(-E_x/40\ \mathrm{keV})\,, \tag{1}$$

If this emission is bremsstrahlung the spectrum of emitting particles should be very hard: $N(E) \propto E^{-\gamma}$ with $\gamma \leq 1$. Just this kind of spectra are expected for stochastic acceleration.

2 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 and 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 $n \simeq 8 \cdot 10^{-2}$ 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 whose spectrum is formed by Coulomb collisions.

The equation for stochastic acceleration and Coulomb collisions has the form

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

where τ and u are the dimensionless time and the particle velocity. The parameter $A(u)$ describes particle diffusion due to Coulomb collisions and the stochastic acceleration, and $B(u)$ describes particle ionization losses.

The acceleration due to the particle interaction with chaotic electromagnetic turbulence is described as momentum diffusion with the coefficient

$$\alpha(p) = \alpha_0 u^2 \qquad (3)$$

The equation for the acceleration frequency α_0 can be derived from the balance between the particle flux into the acceleration region dN/dt which is estimated from the observed flux of hard X-rays and the particle escape due to ionization loss, N/τ_i.

The parameters derived for the models of electron and proton bremsstrahlung are presented in Table 1.

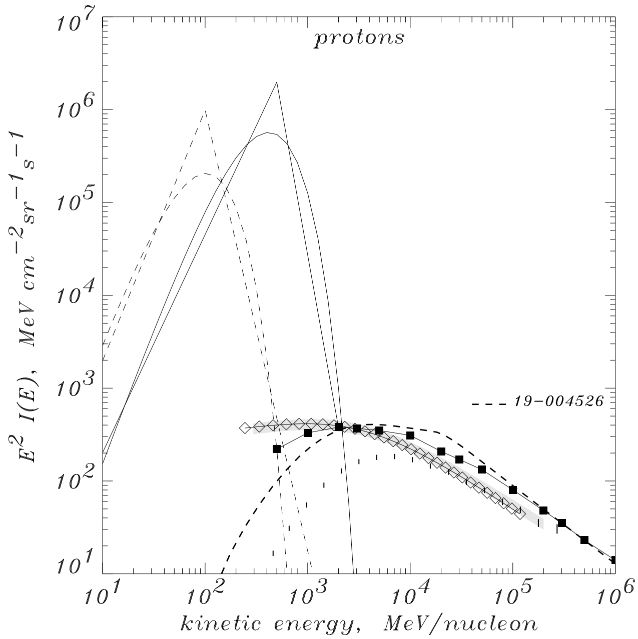

Fig. 1. The function $E^2 \cdot I(E)$ for the observed relativistic and derived subrelativistic spectra of the interstellar protons (solid line - Spectrum I; thin dashed line - Spectrum II), vertical bars - IMAX direct measured spectrum, thick dashed line the proton spectrum derived from the propagation model, connected squares and diamonds, and dashed area - different variants of the proton demodulated spectrum (see Strong et al. 2000). We show also in the figure (triangles) the approximations to Spectrum I and Spectrum II which were used for estimates of the π^o gamma-ray flux produced by the accelerated protons.

Here w is the energy density of the accelerated particles and F is the total luminosity of the subrelativistic particles in the Galaxy.

As follows from analysis of the kinetic equation the production spectrum of accelerated particles is hard and has the form

$$Q(E) = K \cdot E^{-1}\theta(E_{max} - E)\,, \qquad (4)$$

where K is constant, 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.

The following transformation of the injection spectrum of subrelativistic accelerated particles in the interstellar medium is due to processes of ionization energy losses and spatial propagation. 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 $\gamma \leq 1$.

Analysis of the kinetic equation shows that protons are accelerated much more effectively than electrons. This means that in the case of interstellar acceleration it is easier to produce nonthermal protons than electrons. It can also be shown that the flux of accelerated nuclei with $Z > 1$ is strongly suppressed compared to the abundance of elements in the background plasma and therefore the abundances of the back-

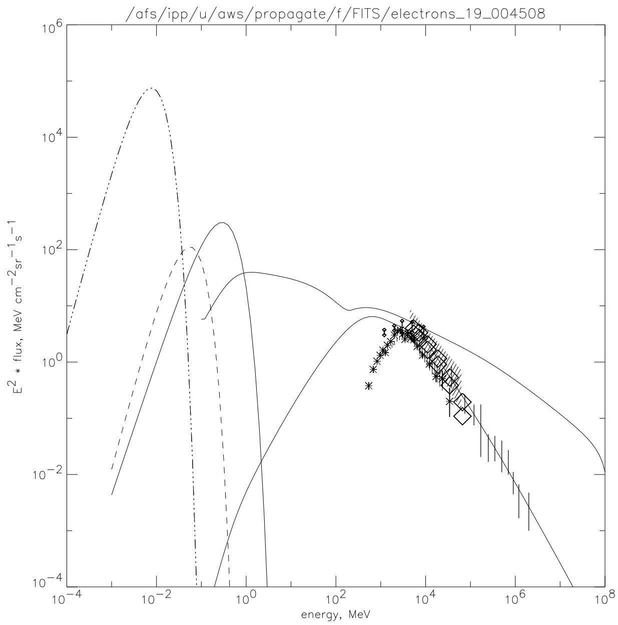

Fig. 2. The function $E^2 \cdot I(E)$ for the observed relativistic and derived subrelativistic spectra of interstellar electrons (solid line - Spectrum I, dashed line - Spectrum II), dashed-dotted-dotted line - the thermal spectrum of electrons. In the relativistic energy range measurement of the electron 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)).

ground gas and that of the accelerated nuclei are quite different.

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. The proton spectra for an exponential cut-off at the energy 150 MeV (dashed line) and for the energy 500 MeV (solid line) are shown in Fig.1.

However, the spectrum shown by the solid line produces too many π^0-photons and the spectrum shown by dashed line generate too high carbon and oxygen gamma-ray line emission.

To avoid these problems of the proton bremsstrahlung model we can assume that the proton spectrum in the central part of the galactic ridge is very hard and has an extremely steep cut-off just near the threshold energy for π^o 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 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^o emission. On the other hand the electron bremsstrahlung model requires more effective acceleration of background particles with the characteristic time $\sim 10^{13}$ s. The acceleration of protons must be

Table 1. Parameters of the accelerated protons (p) and electrons (e)

	N (cm^{-3})	w (eV cm^{-3})	dN/dt (cm^{-3}s^{-1})	τ_i (s)	F (erg s^{-1})
p	$2\cdot10^{-6}$	$250 - 400$	$\sim 10^{-21}$	$2\cdot10^{14}$	$\sim 10^{42}$
e	$2\cdot10^{-6}$	0.2	$\sim 10^{-18}$	10^{13}	$\sim 10^{42}$

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.

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.

The situation may be different at subrelativistic energies since the velocities of electrons v_e and protons v_p producing the bremstrahlung photon with energy E_x are equal to each other, $v_p = v_e$, and therefore the proton Larmor radius r_L^p is much larger than that of electrons r_L^e. We notice that the particle Larmor radius is an essential parameter which affects CR acceleration and propagation (see, e.g., Berezinskii et al. 1990).

Stochastic acceleration effectively generates energetic particles whose Larmor radius is less than the characteristic correlation length of the magnetic turbulence L_c. 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, thus $r_L(E_{max}) \sim L_c$ where E_{max} is the maximum energy of accelerated particles. This effect may explain a preferential subrelativistic electron acceleration emitting hard X-ray if $r_L^e(E_x) < L_c < r_L^p(M/m)E_x$.

3 Conclusion

In conclusion we confirm the importance of the analysis of the X-ray diffuse emission in the hard energy range. This analysis allows to cover the gap between the spectrum of relativistic cosmic rays measured near Earth and the spectrum of thermal interstellar plasma and thus determine the flux of subrelativistic cosmic rays which cannot be directly measured in the interplanetary medium.

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