Contribution of basic processes to diffuse gamma-ray flux from neighbouring galaxies

S.Yu. Matveev, S.R. Kelner, R.P. Kokoulin and A.A. Petrukhin

Moscow Engineering Physics Institute (State University), 115409, Moscow, Russia

Abstract. **Measurements of diffuse gamma-ray flux from neighbouring galaxies give a good possibility of distinguishing between two hypotheses of origin of cosmic rays with energy above 1 GeV (galactic or metagalactic). Well-known experimental data of EGRET gamma-ray telescope and results of theoretical calculations (f.e., for SMC) do not conradict these hypotheses because of insufficient accuracy of both results. Taking into account that in near-term future new experimental data from GLAST and AGILE will be obtained, the accuracy of corresponding theoretical calculations will be of a crucial importance to choose between the alternative hypotheses. In this paper, contributions of neutral pion decays and electron bremsstrahlung to diffuse gamma-ray flux with energy above 100 MeV are considered.**
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I. INTRODUCTION

At calculations of diffuse gamma-ray flux with energy above 100 MeV from the nearest galaxies it is usually assumed (for example, [1]) that this flux at such energies is formed mainly due to the decays of neutral pions, which are born in interactions of primary particles of cosmic radiation with the interstellar gas (hydrogen). The bremsstrahlung of electrons/positrons is the second in the significance process; however, the estimations of its contribution to the diffuse gamma-ray flux with the energy above 100 MeV strongly differ: from ones to tens percent (for example, [1] and [2]). On the one hand, such a strong spread is caused by a deficiency of knowledge about the cross section of production of charged pions, which are the source of secondary electrons/positrons, at pp-interactions of primary cosmic ray particles with the interstellar gas. On the other hand, the uncertainties of adopted parameters (magnetic field, distribution of densities of interstellar gas and supernovaes, etc.) significantly influence results of calculations of electron spectrum in other galaxies.

In the works [3,4] the analysis of uncertainties in the calculations of the diffuse gamma-ray flux from the neutral pion decays was carried out. It was shown that earlier calculation results were overestimated and the calculation method considering separate channels of the neutral pion generation at total number of pions up to $n = 3$ inclusive was proposed. In the present work the estimation of the gamma-ray flux from bremsstrahlung of secondary electrons/positrons from pion decays generated in pp-interactions is carried out. The compari-son of the gamma-ray flux from the secondary electrons/positrons bremsstrahlung and neutral pion decays is done. In contrast to the previous work [4] the energy distribution of pions was calculated on the basis of the phase volume of the final state.

II. GENERATION SPECTRA OF PIONS

For calculations of the differential spectra of pions the following equation is usually used ($s^{-1}sr^{-1}MeV^{-1}$(H atom)$^{-1}$):

$$J_\pi(T_\pi) = \int_{T_{p_{\min}}}^{\infty} \langle \zeta_\pi \sigma_\pi(T_p) \rangle \, W_\pi(T_p, T_\pi) J_p(T_p) dT_p, \quad (1)$$

where $J_p(T_p)$ is primary proton spectrum; $\langle \zeta_\pi \sigma_\pi(T_p) \rangle$ is inclusive cross section of pion production; $W_\pi(T_p, T_\pi)$ is probability distribution of generation of pion with energy T_π at interaction of proton with energy T_p. In general, the function $W_\pi(T_p, T_\pi)$ depends also on particle multiplicity (for example, the number of pions) in a final state. At calculations of the function $W_\pi(T_p, T_\pi)$ it is usually assumed that this function is mainly determined by only one pion in the final state (see, for example, [2]). In our calculations we will also proceed from this assumption; however, the estimations show that this approximation can lead to a distortion of pion spectra in the region of low energies (≤ 200 MeV), especially in the case of generation of negative pions.
On the basis of the phase volume of final particles [5], the pion distribution in the kinetic energy in the laboratory system can be written in the form:

$$W_\pi(T_p, T_\pi) =$$
$$\frac{\kappa}{2m_p \Gamma \sqrt{\kappa^2 - 1}} \int_{y_{min}}^{y_{max}} \sqrt{\frac{\kappa^2 + \rho^2 - 1 - y}{\kappa^2 + \rho^2 - y}} dy, \quad (2)$$

where

$$\Gamma = \int_{y1_{min}}^{y1_{max}} \sqrt{y^2 - 4\kappa^2 \rho^2} \sqrt{\frac{\kappa^2 + \rho^2 - 1 - y}{\kappa^2 + \rho^2 - y}} dy. \quad (3)$$

In these equations $\kappa = \sqrt{s}/2m_p$; $\rho = m_\pi/2m_p$; m_p and m_π are masses of proton and pion, correspondingly. $\sqrt{s}$ is total energy of colliding protons in cenrte-of-mass frame (c.m.f.). The integration limits are found from kinematic limitations of the angle between pion and proton momenta in c.m.f. In Fig. 1, the differential spectra of pions, calculated on these formulas are shown.

The inclusive cross sections of pion generation was taken from the work [6]. The used here spectrum of protons is the approximation [4] of experemental data on the proton flux near the Earth ($cm^{-2}s^{-1}sr^{-1}MeV^{-1}$):

$$J_p(T_p) =$$
$$10^{-3} \cdot \left(1 - \left(\frac{m_p}{T_p + m_p}\right)^2\right) \cdot \left(\frac{T_p + m_p}{m_p}\right)^{-2.73}. \quad (4)$$
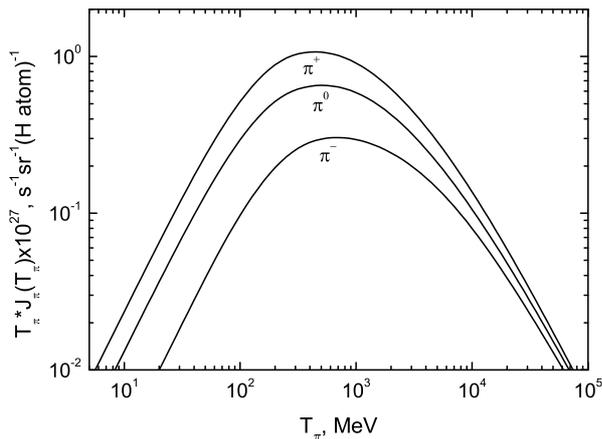

Fig. 1: Differential pion spectra.

III. SECONDARY ELECTRON/POSITRON SPECTRA

For determining the electron/positron energy spectra $J_e(E_e)$, further the electrons if not stipulated the opposite, at a certain point of a galaxy (metagalaxy) it is necessary to know electron sources in its environment, the rate of electron diffusion, the magnetic field strength and the density of the interstellar gas. In general, all these parameters may have fairly complicated distributions and they will be different for different types of galaxies. At the calculation of the diffuse gamma-ray flux from the neighbouring galaxies, assuming that the electrons do not leave the galaxy, and also assuming the gradients of magnetic field and density of interstellar gas be not very large, from the point of view of strange observer the electron diffusion can be disregarded. Then, in the approximation of continuous energy loss, kinetic equation for determining the spectra of electrons and positrons may be written down in the form:

$$\frac{\partial}{\partial E_e}(b(E_e)J(E_e)) = Q_e(E_e) - w(E_{e+})J(E_{e+}). \quad (5)$$

Function $b(E_e) = |dE_e/dt|$ determines the electron energy loss per unit time, $Q_e(E_e)$ is the source function. The second term in the right side of the equation (5) is used only at calculations of the positron spectrum and considers their annihilation.

Let us in this work examine the generation of only secondary electrons from pp-interaction of cosmic ray particles with the interstellar gas (protons). We will assume the density of protons and electrons of interstellar

gas equal to $N_p = N_e = 1$ cm^{-3}, and the magnetic field induction equal to 10^{-5} Gs. The differential spectrum of generation of electrons from pp-interaction takes the form:

$$Q_e(E_e) = \int_{E_e + m_\pi^2/4E_e}^{\infty} f_e(\gamma_e, \frac{E_e}{E_\pi})J_\pi(E_\pi)\frac{dE_\pi}{E_\pi}. \quad (6)$$

The function $f_e(\gamma_e, E_e/E_\pi)/E_\pi$ determines probability that upon pion decay the energy of electron/positron will be concluded in the interval $(E_e, E_e + dE_e)$. In our work calculations of this function are analogous to ones given in the work [7]. Essential difference consists only in the fact that the generalization to all possible energies (not only ultrarelativistic [7]) was used. At calculations of the energy loss $b(E_e)$ the bremsstrahlung and synchrotron radiation were considered; energy loss due to inverse Compton scattering on relict photons and collisions with electrons of interstellar gas were not taken into account:

$$b(E_e) = cN_pE_e \int_0^1 \nu\sigma(\gamma_e, \nu)d\nu + \frac{4e^4}{9m_e^2c^3}\gamma_e^2B^2. \quad (7)$$

The first term in equation (7) describes energy loss caused by the bremsstrahlung, its cross section was taken from the work [8]. The second term corresponds to energy loss for synchrotron radiation in the chaotic magnetic field with the induction B. In this equation c is the speed of light, $\nu = E_\gamma/E_e$, e is electron charge.
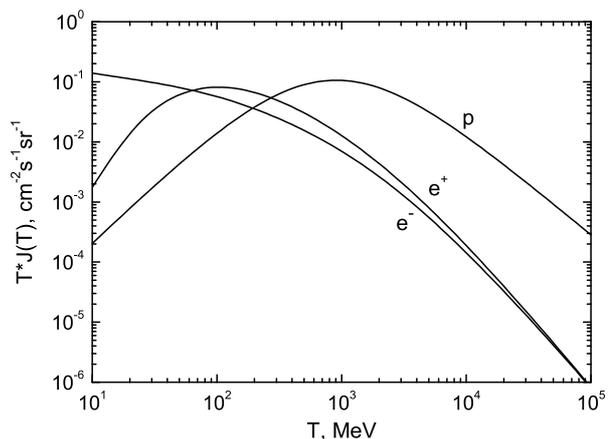

Fig. 2: Differential spectra of secondary electrons.

In the case of positrons it is necessary to consider their annihilation with the electrons of interstellar gas. The probability of this process per unit time is determined by the expression $w(E_{e+}) = N_e v\sigma(E_{e+})$, where v is the speed of positron, and the total cross section of the annihilation $\sigma(E_{e+})$ is taken from [8]. In Fig. 2 the spectra of electrons and positrons calculated by means of the above equations are presented, the approximation (4) of the spectrum of protons of cosmic radiation near the

Earth according to the data [9] is shown for comparision. The bend of the positron spectrum in the region of low energies is caused by their annihilation with the electrons. Magnetic field ($B = 10^{-5}$ Gs) leads to a steepening of the spectra of electrons and positrons beginning from the energy about 100 MeV.

IV. GAMMA-RAY SPECTRA FROM DIFFERENT PROCESSES

The differential spectra of photons from the neutral pion decays, the electron/positron bremsstrahlung and annihilation of positrons are calculated by the following equations, respectively:

$$J_\gamma(E_\gamma) = 2 \int_{E_{min}}^{\infty} \frac{J_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} dE_\pi, \qquad (8)$$

$$J_\gamma(E_\gamma) = c N_p \int_{E_\gamma}^{\infty} \sigma(\gamma_e, v) J_e(E_e) \frac{dE_e}{E_e}, \qquad (9)$$

$$J_\gamma(E_\gamma) = c N_e \int_{E_{e_{\min}}}^{\infty} \sigma(E_e, E_\gamma) J_e(E_e) dE_e. \qquad (10)$$

The cross sections in formulae (9, 10) are taken from [8]. In equation (8), the lower limit is $E_{min} = E_\gamma + m_\pi^2/4E_\gamma$; in equation (10) $E_{e_{\min}} = m_e(2k^2 - 2k + 1)/(2k - 1)$, where $k = E_\gamma/m_e$. The spectra $J_\pi(E_\pi)$ and $J_e(E_e)$ are determined earlier. In Fig. 3 the integral spectra of photons from these processes giving the contribution to the diffuse flux of gamma-radiation are shown. In the case of electron/positron bremsstrahlung it was assumed that electrons do not leave the galaxy and completely dissipate the energy in radiation, therefore the presented spectrum gives an upper limit of contribution of this process. In calculations, the contribution from interactions of nuclei and generation of gamma-quanta through other mesons, which may give the correction factor ~ 2 [3] was not taken into account.
From Fig. 3 one can see that at the energy 100 MeV the upper limit of gamma-ray flux from the bremsstrahlung is near the flux from neutral pion decays and it is not possible to disregard it. More impotant point is the fact that gamma-quanta only from the secondary electrons are taken into account, and according to the estimations [10], at least in our Galaxy, the gamma-ray flux from primary electrons is several times more than from the secondary ones (from the center of Galaxy). If we expect a similar situation for other galaxies, in particular for Large and Small Magellanic Clouds, then the registration of the diffuse gamma-ray flux with energies of less than $\sim$ 300 MeV will bear information mainly about the density of the sources of the primary electrons. Therefore, for the reliable estimation of the flux of primary cosmic radiation (protons) by means of the registration of the diffuse gamma-ray flux from other galaxies it is necessary to use measurements of diffuse flux with higher energies (above 300-500 MeV).
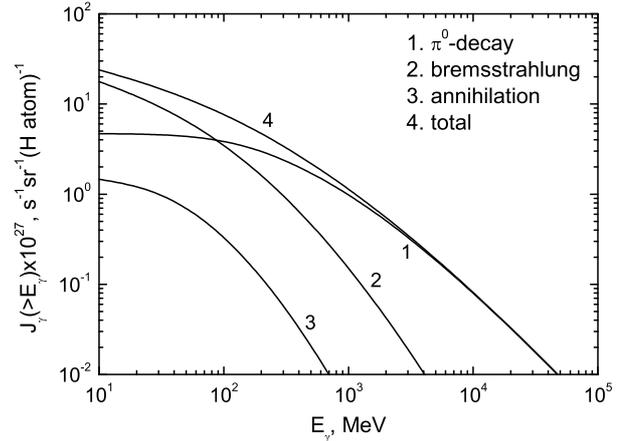

Fig. 3: Contribution of different processes to the diffuse gamma-ray flux. The magnetic field induction equals to 10^{-5} Gs; density of interstellar gas 1 cm^{-3}.

V. CONCLUSION

Under assumptions that the density of protons and electrons in the interstellar medium is constant, 10^{-5} Gs magnetic field, and total dissipation of electron/positron energy in the galaxy the spectra of photons from different processes of their generation were obtained. It is shown, that the contributions of gamma-quanta from secondary electron/positron bremsstrahlung and neutral pion decays to diffuse gamma-ray flux at energies above 100 MeV are nearly equal. Taking into account the contribution of bremsstrahlung from the primary electrons, it is possible to draw the conclusion that for testing the hypotheses about the galactic or metagalactic origin of cosmic rays the measurements of diffuse gamma-ray flux with energies more than 300-500 MeV are necessary.

VI. ACKNOWLEDGMENTS

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