SOVIET PHYSICS USPEKHI VOLUME 7, NUMBER 5 MARCH-APRIL 1965
523+537.531

SOME PROBLEMS OF GAMMA AND X-RAY ASTRONOMY

V. L. GINZBURG and S. I. SYROVAT-SKIĬ

Usp. Fiz. Nauk 84, 201-242 (October, 1964)

INTRODUCTION

GAMMA astronomy, which is presently in its initial development stage, will undoubtedly prove to be an important method of outer-space research. This conclusion can be drawn, first, from general considerations: any extension of the spectrum of electromagnetic waves used in astronomy has always led to major results. Second, there is concrete evidence in favor of the great value of the information that can be obtained in principle as a result of reception of cosmic gamma rays. This pertains also to the field of x-rays (x-ray astronomy). In the latter case, a considerable amount of information has already been obtained for the sun[1,2]. A flare of solar gamma rays was also observed[3]. The experimental material on cosmic gamma and x-rays of non-solar origin is still very skimpy, for only a few measurements were made of the x-ray intensity[4,69], and only an upper limit was indicated for the gamma ray intensity[5,6] (for more details see Secs. 4.3 and 5.3).

In this article we discuss different mechanisms for the production of gamma rays and estimate the efficiency of these mechanisms in the galaxy, in individual galactic and extra-galactic nebulas, and in metagalactic space. We shall focus our main attention on gamma rays produced by cosmic rays[7-17], for on the one hand, it is this gamma radiation which plays the principal role and, on the other hand, in many cases we have definite cosmic-ray information from independent sources (radioastronomy, investigation of cosmic rays on earth). If information is available on the particles generating the gamma rays, an analysis of the gamma-astronomy data is much simpler. In fact, the gamma-ray intensity is determined by the product of the cosmic-ray intensity and the mass of the material or the energy of the optical radiation per unit area along the line of sight. As to the energy spectrum of the gamma rays, it depends in practice only on the cosmic-ray spectrum. It is clear therefore that the use of cosmic-ray data can be of decisive significance for the understanding of the origin and characteristics of cosmic gamma rays.

Another obvious aspect is that measurement of the intensity and spectrum of the gamma rays can serve as a source of information on the cosmic rays themselves. Of particular value is the possibility of studying in this manner the cosmic rays in metagalactic space. The magnetic fields are in this case so weak that the relativistic electrons and positrons, which constitute the electronic component of the cosmic rays, do not produce noticeable cyclotron radio emission. However, the same relativistic electrons should produce gamma rays when they are scattered by the optical photons present in the galaxy (we are speaking primarily of radiation from the stars). This uncovers an inestimable possibility of obtaining information on cosmic rays in the galaxy with the aid of gamma astronomy.

The situation becomes to a certain degree more complicated in the x-ray band, since the particles that generate the x-rays can essentially possess a low energy, say smaller than 10^8 eV (we shall call these subcosmic particles).* We have practically no information whatever on subcosmic particles far away from the earth, apart, say, from the subcosmic-energy positrons induced by cosmic rays. Of course, this does not make galactic x-ray astronomy less interesting in this connection. Nevertheless, the approach to the problem as a whole must be somewhat different than in the case of gamma astronomy. An exception is the cyclotron-radiation component of the cosmic x-radiation, for which the cosmic rays are wholly responsible.

In this article we shall discuss x-ray astronomy essentially only in connection with cosmic rays, that is, we shall consider the contribution made by these rays to the intensity of the x-radiation coming from outer space. The article is thus devoted only to gamma and x-radiation generated by cosmic rays.

1. RADIATION MECHANISMS

1.1. Processes Leading to the Production of Gamma and X Rays

Cosmic rays generate high-energy electromagnetic radiation as a result of the following processes.

1. Decay of the neutral pions produced by cosmic rays in the interstellar medium ($\pi^0 \rightarrow \gamma + \gamma$). Inasmuch as both the cosmic rays and the interstellar gas are made up essentially of hydrogen (approximately 90% of the number of nuclei), it is sufficient in the first approximation to consider the generation of neutral pions in p-p interactions. For cosmic rays of very high energy, such production of π^0 mesons becomes possible through collision with photons of visible light (pion photoproduction). The energy threshold of pion photoproduction from nucleons at rest is approximately 150 MeV; therefore (see below) in the case of photoproduction of pions from thermal photons with average energy ~ 1 eV the cosmic-ray energy should exceed 10^{17} eV/nucleon.

2. Bremsstrahlung of relativistic electrons (and positrons) making up the electronic component of the cosmic rays. This effect is $(M/m)^2$ times smaller for relativistic protons than for electrons having the same energy. Therefore, although there are approximately 10^2 times as many protons in cosmic rays than electrons, the bremsstrahlung of the protons can be neglected. The radiation accompanying the production of electrons and positrons as a result of the $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$ decay can also be regarded as bremsstrahlung, as well as the radiation produced when δ-electrons are produced by cosmic rays in the interstellar gas.

3. Compton scattering of relativistic electrons by thermal photons radiated from the stars (this is sometimes called the inverse Compton effect). As in the case of bremsstrahlung, the contribution of relativistic protons is negligibly small in this case.

4. Annihilation of positrons ($e^+ + e^- \rightarrow 2\gamma$) in interstellar gas. A distinction must be made here between the annihilation of relativistic positrons in flight, which leads to gamma radiation with a continuous spectrum, and to the annihilation of stopped positrons. In the latter case the radiation is monochromatic ($E_\gamma = mc^2 \simeq 0.51$ MeV) and can be distinguished by means of this attribute against the background of the continuous spectrum.*

5. Nuclear gamma rays produced in interactions between cosmic rays in interstellar gas as a result of excitation of nuclei and of their fragments.

The foregoing processes, caused by cosmic rays, lead to the formation of gamma radiation in the interstellar medium. In addition, gamma rays can be generated in the stellar atmospheres both as a result of nuclear reactions and under the influence of the fast particles produced in the same atmospheres. In the former case (nuclear reactions in which relatively slow particles participate) the gamma-ray spectrum will be essentially discrete, and in the latter case continuous. Of course, gamma radiation of stellar atmospheres must be investigated first with the sun as an example, predominantly during the time of solar flares (see [2,3,19,19a] in this connection).

A special place is occupied by neutron stars and quasars. Hot neutron stars can be powerful sources of thermal x-radiation[20-22]. Quasars should produce powerful gamma radiation[23], provided that their optical radiation has a cyclotron-resonance nature. In addition, noticeable cyclotron x-radiation can be produced near collapsed magnetic stars[24] (such radiation can, of course, arise also in the main part of supernova envelopes, provided that they contain electrons of sufficiently high energy).

Some of the processes mentioned above (processes 2 and 3) are important also in the x-ray region of the

*Subcosmic particles also produce soft gamma rays. This gamma-radiation component, however, will be disregarded here unless specially stipulated.

*We note that the presence of a considerable amount of antimatter especially positrons, in interstellar space could be detected in principle by means of the optical lines of positronium in the visible part of the spectrum [18]. It is evident, however, that the corresponding energy flux in the optical range will be incomparably smaller than the energy flux of the annihilation gamma quanta. When it comes to the number of photons, its order of magnitude is the same in both cases.

spectrum. However, the greatest contribution to this region can be made not by cosmic but by subcosmic rays (kinetic energy $E_c \lesssim 10^8$ eV). Of course, this will occur only if the intensity of the subcosmic rays is sufficiently large[25,26]. Inasmuch, as already mentioned in the introduction, there are still practically no data on subcosmic rays, we shall only indicate the lower limit of x-ray intensity, taking into account processes 1, 2, and 3 which are due to cosmic rays. At the same time, we must keep in mind still another mechanism of x-ray emission. We refer here to cyclotron x-radiation from high energy electrons in interstellar magnetic fields.

1.2. General Expressions for the Radiation Intensity

We shall be interested in the gamma-ray intensity $I_\gamma(E_\gamma)$, defined as the number of gamma quanta normally incident on a unit area per unit time in a unit solid angle and unit energy interval. For the gamma rays induced by cosmic rays of isotropic intensity $I(E)$, the intensity $I_\gamma(E_\gamma)$ is determined in the following fashion. The total number of gamma rays with energies in the interval E_γ, $E_\gamma + dE_\gamma$, produced per unit volume and per unit time, is

$$\tilde{q}(E_\gamma)\,dE_\gamma = 4\pi q(E_\gamma)\,dE_\gamma = 4\pi n(\mathbf{r})\,dE_\gamma \int_{E_\gamma}^{\infty} \sigma(E_\gamma, E)\,I(E)\,dE, \qquad (1.1)$$

where $q(E_\gamma) = \tilde{q}(E_\gamma)/4\pi$ —number of gamma quanta produced per unit solid angle, $n(\mathbf{r})$ —concentration of the atoms at the point $\mathbf{r}$, and

$$\sigma(E_\gamma, E)\,dE_\gamma = dE_\gamma \int \sigma(E_\gamma, E, \Omega)\,d\Omega$$

—cross section, integrated over the emission angles, for the production of a gamma quantum with energy in the interval E_γ, $E_\gamma + dE_\gamma$ by a particle of energy E.

The radiation flux within a solid angle $d\Omega$ is therefore

$$dF_\gamma(E_\gamma) = I_\gamma(E_\gamma)\,d\Omega = d\Omega \int_0^L \frac{\tilde{q}(E_\gamma)}{4\pi r^2}\,r^2\,dr = d\Omega \int_0^L q(E_\gamma)\,dr$$

or

$$I_\gamma(E_\gamma) = \int_0^L q(E_\gamma)\,dr = N(L) \int_{E_\gamma}^{\infty} \sigma(E_\gamma, E)\,I(E)\,dE, \qquad (1.2)$$

where

$$N(L) = \int_0^L n(\mathbf{r})\,dr$$

is the number of gas atoms along the line of sight [in the case of the Compton effect it is necessary to use in lieu of $N(L)$ the number of photons $N_{ph}(L)$]. In (1.2) the cosmic-ray intensity is assumed to be the same over the entire path L.

The intensity (1.2) is usually called the differential gamma-ray spectrum. The integral spectrum is then given by

$$I_\gamma(>E_\gamma) = \int_{E_\gamma}^{\infty} I_\gamma(E_\gamma)\,dE_\gamma. \qquad (1.3)$$

In the case of discrete sources whose dimensions are small compared with the distance from the point of observation to the source R, it is more convenient to use not the intensity but the flux

$$F_\gamma(E_\gamma) = \int_\Omega I_\gamma(E_\gamma)\,d\Omega \simeq \frac{N_V}{R^2} \int_{E_\gamma}^{\infty} \sigma(E_\gamma, E)\,I(E)\,dE, \qquad (1.4)$$

where the first integral is taken over the solid angle occupied by the source, and

$$N_V = R^2 \int_\Omega N(L)\,d\Omega \approx \int n(\mathbf{r})\,dV$$

is the total number of gas atoms in the source.

Sometimes one uses not the gamma-quantum intensity but the energy flux $d\Phi_\gamma = J_\gamma(E_\gamma)d\Omega$. The corresponding differential and integral "energy" intensities are defined by

$$J_\gamma(E_\gamma) = E_\gamma I_\gamma(E_\gamma) \qquad (1.5)$$

and

$$J_\gamma(>E_\gamma) = \int_{E_\gamma}^{\infty} E_\gamma I_\gamma(E_\gamma)\,dE_\gamma. \qquad (1.6)$$

Before we proceed to an estimate of the effectiveness of each of the foregoing mechanisms for the interstellar and intergalactic space, we present data on the cosmic rays, amount of matter, and energy density of thermal radiation in the galaxy and metagalaxy.

2. COSMIC RAYS, MATTER, AND THERMAL RADIATION IN THE UNIVERSE

2.1. Intensity of Cosmic Rays

In the energy interval 10 BeV < E < 10^6 BeV, the cosmic ray intensity is characterized by a power-law dependence on the energy, the exponent of the differential energy spectrum being[27-30] $\gamma = 2.6-2.7$. We shall assume that $\gamma = 2.6$; this, together with the recently measured[31] absolute value of the intensity of the protons near the geomagnetic equator I_p (E > 16.8 BeV) = 88 ± 12 m^{-2} sec-sr^{-1}, corresponds to a proton-energy spectrum

$$I_p(E) = 1.3E^{-2.6}\,\frac{\text{protons}}{\text{cm}^2\ \text{sec}\cdot\text{sr}\cdot\text{BeV}}, \qquad (2.1)$$

where $E = (M^2c^4 + c^2p^2)^{1/2}$ is the total energy.

According to the available data, the nuclear composition of the cosmic rays is constant in the indicated energy interval, and is the same as at an energy E = 2–3 BeV/nucleon (see, for example, [32]). The number of nucleons with specified energy, contained among the alpha particles and heavier nuclei, is about 40% of the number of protons having the same energy. Thus, the total intensity of nucleons having energies in the interval E, E+dE is equal to

$$I_N(E)\,dE = 1.8E^{-2.6}\,dE\,\frac{\text{nucleons}}{\text{cm}^2\ \text{sec}\cdot\text{sr}\cdot\text{Bev}}. \qquad (2.2)$$

With decreasing energy, at $E < 10$ BeV/nucleon, the intensity increases more slowly than $E^{-2.6}$, and passes through a maximum at a rigidity[33] $R = cp/eZ \approx 1.6$ BeV, that is, at an energy $E \simeq 2$ BeV for protons and $E \simeq 1.3$ BeV/nucleon for nuclei with $A = 2Z$. The total intensity of the protons on earth during the period of the minimum solar activity is

$$I_p \simeq 0.20\,\frac{\text{nucleons}}{\text{cm}^2\ \text{sec}\cdot\text{sr}}; \qquad (2.3)$$

and the fraction of the nucleons relative to all the remaining nuclei is approximately the same.

In the region of superhigh energies $E > 10^6$ BeV $= 10^{15}$ eV, the character of the spectrum changes and, at least up to an energy $E \sim 10^{18}$, the intensity decreases more rapidly[34], with an exponent $\gamma \simeq 2.1 \pm 0.1$. The chemical composition of the cosmic rays at these energies has been hardly studied so far.

The foregoing values pertain to the intensity measured on earth. In accordance with present-day notions[32], we assume that the cosmic rays fill sufficiently uniformly the entire galaxy, including the halo, that is, a quasispherical volume with radius $R \simeq 5 \times 10^{22}$ cm (volume $V \simeq 5 \times 10^{68}$ cm^3).

There is presently no direct information whatever on the intensity of the cosmic rays in metagalactic space. We shall therefore assume that the intensity of the cosmic rays in the metagalaxy differs only by a factor $\xi_{\text{c.r.}}$ from the galactic intensity, that is,

$$I_{\text{Mg}}(E) = \xi_{\text{c.r.}} I_{\text{g}}(E), \qquad (2.4)$$

where $I_g(E)$ is taken to be the nucleon intensity (2.2) in the galaxy. As to the factor $\xi_{\text{c.r.}}$ itself, its most convincing estimate is based in fact on gamma-astronomy data (see Sec. 4).

2.2. Electronic Component of Cosmic Rays

The available data on the electronic component of cosmic rays in the galaxy are based on radioastronomic findings and on the results of measurements of the intensity of the electrons on earth. According to the cyclotron-radiation theory of galactic radio emission[32], the spectral index of radio emission α is connected with the exponent γ_e of the energy spectrum of the electrons by the relation

$$\gamma_e = 2\alpha + 1, \qquad (2.5)$$

and it can be assumed in first approximation that the main contribution to the radiation at a frequency ν is made by electrons with energies*

$$E = 4.7\cdot 10^2 \sqrt{\frac{\nu}{H_\perp}}\ \text{eV}, \qquad (2.6)$$

where the frequency ν is in cps, and the magnetic field component $H_\perp$ perpendicular to the line of sight is in oersted.

In the interval $10^7 - 3 \times 10^8$ cps, the spectral index of the over-all radio emission of the galaxy is[35,36] $\alpha \simeq 0.5$. Consequently, the exponent of the electron spectrum is $\gamma_e \simeq 2$ in the interval 0.8–5 BeV if, as is most probable, the average for the interstellar space is $H_\perp \simeq 3 \times 10^{-6}$ Oe.

According to [37], the experimental value of the electron intensity on the top of the earth's atmosphere is

$$I_e(E > 1\,\text{BeV}) \approx 1.5\cdot 10^{-3}\,\text{cm}^{-2}\text{sec}^{-1}\text{sr}^{-1}.$$

The measurements of [37] were made during the period of high solar activity, when the intensity of protons having the same magnetic rigidity was 2–3 times higher than its value during the period of the solar minimum. An analogous decrease apparently took place also for the electrons. We can therefore assume tentatively for the intensity of the electrons, beyond the limits of the solar system but in the adjacent region of the galaxy, a value

$$I_e(E) = 5\cdot 10^{-3} E^{-2}\,\frac{\text{electrons}}{\text{cm}^2\ \text{sec}\cdot\text{sr}\cdot\text{BeV}}. \qquad (2.7)$$

The intensity (2.7) agrees also with the observed intensity of the over-all galactic radio emission[38], if the electrons more or less evenly fill the entire volume of the galaxy (the value of $I_e(E)$ used in [38] was in the main four times larger than the intensity (2.7), but an acceptable change in the parameters can also yield the spectrum (2.7), as was indeed emphasized in [38,16]). The spectrum (2.7) pertains to the energy interval $0.5 < E < 10$ BeV. At higher energies the electron spectrum (as well as the radio emission spectrum) becomes apparently steeper, but the data for this case are utterly insufficient. It can only be stated that at energies $10^{12}-10^{15}$ eV the electron intensity apparently does not exceed several hundredths of one per cent of the intensity of the primary nucleons having the same energy. Such high-energy electrons would be registered alongside the primary gamma rays and, in particular, they would yield in the energy region $E \gtrsim 10^{15}$ eV extensive air showers that are anomalously poor in muons[16].

It has been established experimentally[39-41] that the number of such showers amounts to not more than $10^{-3}-10^{-4}$ of the number of all showers having the same primary-particle energy.

We note that much light has been cast recently on the question of the origin of the radio-emitting relativistic electrons in the galaxy. The greater part of these electrons is of primary origin, that is, arrives together with the cosmic rays from the sources (most probably from supernova envelopes). As regards the

*Formula (2.6) relates the frequency ν, corresponding to the maximum in the radiation spectrum of an individual electron, with its energy E. For a power-law electron energy spectrum, formula (2.6) slightly exaggerates the value of E (for more details see [32]).

secondary electrons produced in nuclear interactions of cosmic rays in the interstellar medium and subsequent decay of the charged mesons, their contribution is insignificant and decreases with increasing energy. This deduction follows from calculations based on the data on the galactic radio-emission spectrum [38,42], as well as from a direct measurement of the fraction of the positrons in the electronic component of the cosmic rays [43] (in the case of secondary origin, the positrons would make up more than half of the total electronic component, whereas according to [43] their number is less than 20% in the 0.3–1 BeV interval).

2.3. Matter and Thermal Radiation in the Galaxy and Metagalaxy

The bulk of the matter in the galaxy (~ 98%) is concentrated in stars, but this matter is screened by the thin cosmic-ray absorbing surface layer of the star. Therefore, from the point of view of the interactions between cosmic rays and matter of interest to us here, a decisive role is played by the rarefied interstellar gas, the total mass of which in the galactic disc is estimated at $M_g \simeq 3 \times 10^{42}$ g. The interstellar gas consists essentially of hydrogen (~ 90% of the number of atoms) and helium (~ 10%), and is very unevenly distributed in the galaxy—in the form of clouds of neutral and ionized hydrogen, located in a galactic disc of radius ~ 15 kpsec $\simeq 5 \times 10^{22}$ cm and with thickness ~ 300 psec $\simeq 10^{21}$ cm. The mass of the ionized gas in the disc is approximately 5% of the total mass of the gas in this region. The mass of the gas in the galactic-halo —a quasispherical region with radius 15 kpsec, surrounding the stellar galaxy and filled with cosmic rays —is actually unknown; we can only state that the mass of the halo does not exceed the mass of the gas in the disc, and the concentration of the gas in the halo is $n \lesssim 10^{-2}$ cm^{-3}. Therefore we estimate the upper limit of the halo mass to be equal to the mass of the gas in the disc: $M_g = 3 \times 10^{42}$ g, and that the gas in the disc and in the halo has a normal (Gaussian) distribution with corresponding spatial dimensions. It is then easy to calculate [10] the number of gas atoms

$$N(L) = \int_0^L n(\mathbf{r})\, dr$$

and the gas mass

$$M(L) = \int_0^L \varrho(\mathbf{r})\, dr \simeq 2 \cdot 10^{-24} N(L)$$

on the line of sight from an observer situated on earth to the boundary of the galaxy (L —distance to the boundary of the galaxy in the given direction, $n(\mathbf{r})$ and $\rho(\mathbf{r})$ —concentration and density of the gas as functions of the coordinates). The values of N(L) and M(L) for three characteristic galactic directions (the center, anticenter, and galactic pole), and the values of N(L) and M(L) averaged over all directions, are listed in

Table I. Values of L, N(L), M(L), and w_{ph} in the galaxy and in the metagalaxy; L—effective path length, N(L) and M(L)—number of atoms and mass of the gas on the path L in a column 1 cm^2 in cross section, w_{ph} —energy density of thermal radiation

	L, cm	$N(L)$, cm^{-2}	$M(L)$, g/cm^2	w_{ph}, eV/cm^3
Galaxy: in the direction of the center	$7 \cdot 10^{22}$	$3 \cdot 10^{22}$	$6 \cdot 10^{-2}$	0,2
in the direction of the anticenter	$1,5 \cdot 10^{22}$	$6 \cdot 10^{21}$	$1,2 \cdot 10^{-2}$	
in the direction of the pole (including the contribution from the halo)	—	$3 \cdot 10^{20}$	$6 \cdot 10^{-4}$	
averaged over all directions (including the contribution of the halo)	—	$8 \cdot 10^{20}$	$1.6 \cdot 10^{-3}$	0.4
Halo (in the direction of the pole)	$3.5 \cdot 10^{22}$	$1,5 \cdot 10^{20}$	$3 \cdot 10^{-4}$	
Metagalaxy	$R_{ph} = 5 \cdot 10^{27}$	$5 \cdot 10^{22}$	0,1	$2 \cdot 10^{-3}$

Table I. For apparatus with finite angular resolution, the essential quantities are the values $\overline{N(L)}$ and $\overline{M(L)}$ averaged over the solid angle of a receiver oriented in a given direction. For the aforementioned directions and for different solid angles of reception, these averages (more accurately, the integrals over the solid angle $\overline{N(L)}\,\Delta\Omega = \int_{\Delta\Omega} d\Omega \int_0^L n(\mathbf{r}, \Omega)\, dr$) have been calculated in [44].

The most probable values for the metagalactic space (for more detail see [32]) are

$$n = 10^{-5}\,\text{cm}^{-3}, \quad \varrho = 2 \cdot 10^{-29} \frac{\text{g}}{\text{cm}^3},$$
$$N(L) = 5 \cdot 10^{22}\,\text{cm}^{-2}, \quad M(L) = 0.1 \frac{\text{g}}{\text{cm}^2}, \qquad (2.8)$$

where the distance L is chosen equal to the photometric radius of the metagalaxy $R_{ph} = 5 \times 10^{27}$ cm (R_{ph} is the distance over which the frequency is reduced one-half by the red shift).

One cannot exclude the possibility that $n \ll 10^{-5}$ cm^{-3} for the metagalaxy; the opposite inequality is much less probable, from considerations based on relativistic cosmology. The values of (2.8) are therefore more likely to be the upper limits of the concentration and gas density in the intergalactic space.

If some additional estimates are made (allowance for the Compton effect and meson photoproduction), an important role is assumed by the radiation energy density w_{ph} in the galaxy and metagalaxy. For the galaxy, calculations of stellar thermal-radiation energy density [45] yield

$$w_{\text{ph, disc}} = 0.2 \frac{\text{eV}}{\text{cm}^3}, \quad w_{\text{ph, halo}} = 0{,}4 \frac{\text{eV}}{\text{cm}^3}. \qquad (2.9)$$

The radiation density in the galactic disc is somewhat smaller than in the halo over the disc, owing to the interstellar absorption of light.

The value of w_{ph} for the intergalactic space is much less reliable. Estimates based on the average brightness of the galaxies lead to a value[32]

$$w_{\text{ph, Mg}} \simeq 2 \cdot 10^{-3} \frac{\text{eV}}{\text{cm}^3}. \quad (2.10)$$

The density (2.10) is a lower limit, since no account is taken of the possible radiation in the invisible region of the spectrum. Yet there are still no real grounds for assuming the existence of such a radiation with a density greatly exceeding the value given by (2.10).

3. COSMIC GAMMA EMISSION (CALCULATION OF INTENSITY)

3.1. Production of π^0 Mesons and "Pionic" Gamma rays

The intensity of pions of all signs, produced on a unit path by cosmic rays with intensity I(E), is

$$q_\pi(E_\pi)\,dE_\pi = dE_\pi n\sigma \int_{E_\pi}^{\infty} \nu(E, E_\pi) I(E)\,dE. \quad (3.1)$$

Here n —concentration of the atoms in the medium, $\sigma \approx 3 \times 10^{-26}$ cm² —cross section for the interaction of the cosmic rays (in practice, protons; see Sec. 1.1) with the nuclei (protons) of the interstellar medium, $\nu(E, E_\pi)dE_\pi$ —average number of pions produced in the energy interval dE_π by each collision with initial energy E. In view of the isotropic nature of the cosmic rays, the total number of pions with energy in the interval dE_π, produced per unit volume and per unit time, is $4\pi q_\pi(E_\pi)dE_\pi$.

The theoretical form of the function $\nu(E, E_\pi)$ is presently unknown. However, we can confine ourselves in what follows to an approximate expression that agrees with the assumption that the average fraction k of the energy of the primary nucleon transferred to all the pions is $k \approx 1/3$, and the average multiplicity of generation of pions as a function of the energy takes the form[46]

$$\nu(E) = \int \nu(E, E_\pi)\,dE_\pi \approx 3E^{1/4},$$

where E is in BeV. Namely, we use the expression

$$\nu(E, E_\pi) = \nu(E)\,\delta\left(E_\pi - \frac{kE}{\nu(E)}\right) \simeq 3E^{1/4}\delta(E_\pi - 0.1E^{3/4}). \quad (3.2)$$

With the aid of (3.1) and (3.2) we obtain for the spectrum (2.2)

$$q_\pi(E_\pi) = 0.12\sigma n E_\pi^{-2.8} \frac{\text{pions}}{\text{cm}^3\ \text{sec} \cdot \text{sr} \cdot \text{BeV}}, \quad (3.3)$$

where the energy E_π is in BeV. Inasmuch as the π^0 mesons constitute one-third of the total number of mesons, we have

$$q_{\pi^0}(E_\pi) = 0.04\sigma n E_\pi^{-2.8} \frac{\pi^0\text{-mesons}}{\text{cm}^3\ \text{sec} \cdot \text{sr} \cdot \text{BeV}}. \quad (3.4)$$

Expressions (3.3) and (3.4) are subject to a certain error due to the assumptions made concerning the character of pion generation. To estimate the value of this error, let us consider the opposite limiting case, when the main role in the generation process is played by a high-energy pion that carries away a fraction $\alpha \approx 20\%$ of the nucleon energy[47,48]. Putting in (3.1)

$$\nu(E, E_\pi) = \delta(E_\pi - \alpha E), \quad \alpha = 0.2, \quad (3.5)$$

we obtain

$$q_\pi(E_\pi) = 0.14\sigma n E_\pi^{-2.6} \frac{\pi\text{-mesons}}{\text{cm}^3\ \text{sec} \cdot \text{sr} \cdot \text{BeV}}, \quad (3.6)$$

$$q_{\pi^0}(E_\pi) = 0.05\sigma n E_\pi^{-2.6} \frac{\pi^0\text{-mesons}}{\text{cm}^3\ \text{sec} \cdot \text{sr} \cdot \text{BeV}}. \quad (3.7)$$

The main difference between (3.7) and (3.4) is in the exponents, and can lead to a discrepancy of one order of magnitude at $E \simeq 10^5$ BeV = 10^{14} eV. This circumstance must be kept in mind; we shall use henceforth expression (3.4) in the estimates.

Inasmuch as the cosmic ray spectrum (2.2) pertains to energies $E \gtrsim 10$ BeV, the expressions (3.3) and (3.4) hold for energies $E_\pi \gtrsim 1-3$ BeV.

For the total number of π^0 mesons generated on a unit path, numerical calculations yield (see [32], p. 37, and also [44])

$$q_{\pi^0}(E_\pi > m_\pi c^2) = \int_{m_\pi c^2}^{\infty} q_{\pi^0}(E_\pi)\,dE_\pi = 4.8 \cdot 10^{-27} n \frac{\pi^0\text{-mesons}}{\text{cm}^3\ \text{sec} \cdot \text{sr}}. \quad (3.8)$$

The intensity of the gamma rays produced in the $\pi^0 \to 2\gamma$ decay can now be readily determined, bearing in mind that in accordance with the kinematics of this decay (see, for example, [10])

$$q_\gamma(E_\gamma)\,dE_\gamma = \frac{2}{\gamma_\pi} q_{\pi^0}(E_\gamma)\,dE_\gamma, \quad (3.9)$$

where γ_π —exponent of the pion energy spectrum. Then, by virtue of (3.4),

$$q_\gamma(E_\gamma) = 0.03\sigma n E_\gamma^{-2.8} \frac{\text{quanta}}{\text{cm}^3\ \text{sec} \cdot \text{sr} \cdot \text{BeV}}, \quad (3.10)$$

$$q_\gamma(> E_\gamma) = \int_{E_\gamma}^{\infty} q_\gamma(E_\gamma)\,dE_\gamma \simeq 0.02\sigma n E_\gamma^{-1.8} \frac{\text{quanta}}{\text{cm}^3\ \text{sec} \cdot \text{sr}}. \quad (3.11)$$

The intensity of the gamma rays produced along a path L in a certain direction is equal to [see (1.2)]

$$I_{\gamma,\pi^0}(> E_\gamma) = \int_0^L q_\gamma(> E_\gamma)\,dL = 6 \cdot 10^{-28} N(L) E_\gamma^{-1.8}$$

$$= 3 \cdot 10^{-4} M(L) E_\gamma^{-1.8}, \quad (3.12)$$

where

$$N(L) = \int_0^L n\,dr$$

—number of atoms and $M(L) = 2 \times 10^{-24} N(L)$ —mass of the gas along the line of sight (see Table I), where we use for σ the cross section given above for the inelastic interaction, $\sigma \simeq 2 \times 10^{-26}$ cm².

According to (2.2) and (3.12), the ratio of the intensities of the gamma rays and of all the cosmic rays with energy larger than E is

$$\zeta=\frac{I_{\gamma,\,\pi^0}(>E)}{I(>E)}\simeq 5\cdot 10^{-28}N(L)\,E^{-0.2}. \qquad (3.13)$$

As already indicated, the energy dependence $E^{-0.2}$ in this formula has not been reliably established, and we cannot exclude the possibility that the ratio ζ is practically independent of the energy. It is important, however, that in any case the energy dependence is weak, and to change ζ by one order of magnitude it is necessary to change the energy by at least four or five orders.

In addition to the already considered generation of mesons in nuclear collisions between cosmic rays and the interstellar gas, interest is also attached to photoproduction of π^0 mesons in collisions between ultrahigh energy particles and thermal photons. This mechanism, which leads as a result of the π^0-meson decay to the production of gamma quanta of very high energy, was considered in [12] with an aim at interpreting the data on extensive air showers with anomalously low muon content [39,40].

In the nucleon rest frame, the energy threshold of photoproduction corresponds to a photon energy $\epsilon' \approx 150$ MeV. Therefore in the laboratory system (tied to the metagalaxy), in which the average photon energy is $\epsilon \simeq 1$ eV, the protons should have an energy $E > \epsilon' Mc^2/2\epsilon$, that is, a total energy $E > 7\times 10^{16}$ eV (we take account here of the Lorentz transformation

$$\varepsilon'=\varepsilon\frac{E}{Mc^2}\left(1-\frac{v_p}{c}\cos\theta\right),$$

where θ —angle between the directions of the photon and of the proton with velocity v_p). In this energy region, the cosmic-ray spectrum exponent is $\gamma\simeq 3$.

To estimate the intensity of the gamma rays produced by decay of neutral photomesons, we can use formulas (3.1), (3.5), and (3.9), substituting for n the photon concentration n_{ph} and assuming that the photoproduction cross section [49] is $\sigma\simeq 2\times 10^{-28}$ cm^2 and that the fraction of energy carried away by the photon is $\alpha\sim 0.1$ (the produced meson and the photon have approximately equal velocities). We then get from (3.1) and (3.5), for a power law cosmic-ray spectrum,

$$q_{\pi^0}(>E_\pi)=n_{ph}\sigma\alpha^{\gamma-1}I(>E_\pi). \qquad (3.14)$$

Furthermore, according to (3.9)

$$I_\gamma(>E)=\frac{2}{\gamma}I_{\pi^0}(>E)=\frac{2}{\gamma}\int_0^L q_{\pi^0}(>E)\,dL$$
$$=N_{ph}(L)\frac{2}{\gamma}\sigma\alpha^{\gamma-1}I(>E). \qquad (3.15)$$

Hence

$$\frac{I_\gamma(>E)}{I(>E)}=N_{ph}(L)\frac{2}{\gamma}\sigma\alpha^{\gamma-1}\simeq 10^{-30}N_{ph}(L), \qquad (3.16)$$

where

$$N_{ph}(L)=\int_0^L n_{ph}\,dL$$

—number of photons along the line of sight, and where we put in the numerical estimate $\alpha=0.1$, $\gamma=3$, and $\sigma=2\times 10^{-28}$.

3.2. Bremsstrahlung

To estimate the intensity of the bremsstrahlung of the relativistic electrons (and positrons) contained in the cosmic rays we can use the approximate expression for the differential effective cross section [50]

$$\sigma_r(E,E_\gamma)\,dE_\gamma=\frac{M}{t_r}E_\gamma^{-1}\,dE_\gamma, \qquad (3.17)$$

where t_r —radiation length unit in a gas of atoms with mass M. For the interstellar medium we assume $M = 2\times 10^{-24}$ g and $t_t \simeq 66$ g/cm^2 (see [51]). The intensity of the bremsstrahlung gamma quanta is then

$$I_{\gamma,\ br}(E_\gamma)=\int_0^L dr\int_{E_\gamma}^\infty n(\mathbf{r})\,\sigma_r(E,E_\gamma)\,I_e(E,\mathbf{r})\,dE \qquad (3.18)$$

or, assuming that the electron intensity along the ray L is constant,

$$I_{\gamma,\ br}(E_\gamma)=\frac{MN(L)}{t_r}\frac{I_e(>E_\gamma)}{E_\gamma}=1.5\cdot 10^{-2}M(L)\frac{I_e(>E_\gamma)}{E_\gamma}. \qquad (3.19)$$

For the spectrum (2.3) we obtain therefore

$$I_{\gamma,\ br}(E_\gamma)=8\cdot 10^{-5}M(L)E_\gamma^{-2},$$
$$I_{\gamma,\ br}(>E_\gamma)=8\cdot 10^{-5}M(L)E_\gamma^{-1}. \qquad (3.20)$$

Here E_γ is in BeV. Comparing this intensity with the intensity (3.12) of the gamma rays from π^0-meson decay we get

$$\frac{I_{\gamma,\ br}(>E_\gamma)}{I_{\gamma,\,\pi^0}(>E)}\simeq 0.3E_\gamma^{0.6-0.8}. \qquad (3.21)$$

From (3.21) we see that in the gamma-quantum energy region not exceeding several BeV the bremsstrahlung is weaker than the radiation produced by π^0-meson decay. At the same time, at higher energies the bremsstrahlung could predominate if the electron spectrum (2.3) were to be valid also in the energy region $E > 10$ BeV. Actually, however, at high energies the electron spectrum apparently becomes steeper (otherwise at $E\approx 10^{11}$ eV the electrons would already amount to approximately 10% of the number of protons in the composition of the cosmic rays), and we can therefore assume that the bremsstrahlung in the entire energy region $E \gtrsim 10^8$ does not exceed the gamma radiation due to π^0-meson decay.

Let us now stop to discuss the radiation produced when electrons and positrons are generated in $\pi^\pm\to\mu^\pm\to e^\pm$ decay. Estimates show (see [16]) that this radiation is approximately two orders of magnitude lower in intensity than the radiation from the $\pi^0\to 2\gamma$ decay. Without repeating the calculations, we merely point out that this result becomes clear if we recognize that the number of gamma quanta produced in nuclear collisions followed by direct decay of the produced mesons ($\pi^0\to 2\gamma$ decay) is approximately the same as that of electrons of both signs (from the $\pi^\pm\to\mu^\pm\to e^\pm$ decays). Inasmuch as the probability of emission of a quantum upon production of an electron contains the additional factor $\alpha = e^2/\hbar c = 1/137$, the intensity of such quanta will be accordingly lower than the intensity of the quanta from $\pi^0 \rightarrow 2\gamma$ decay, and can be disregarded in the subsequent estimates.

Fast electrons are produced also in the form of δ-electrons. By estimating the number of higher-energy δ-electrons produced by cosmic rays, we can readily verify that the contribution of the δ-electrons in sufficiently hard gamma radiation is even lower than the contribution of the $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ decay products. It is sufficient to state that the total number of secondary electrons with energy E exceeding 5×10^7 eV and produced along the line of sight is $Q(E > 5 \times 10^7 \text{ eV}) \sim 3 \times 10^{-2} M(L)$ (see [16,38]), while the number of δ-electrons is $Q(E > 5 \times 10^7 \text{ eV}) \approx 10^{-5} M(L)$.

3.3. Compton Gamma Rays

In collisions between relativistic electrons and light quanta in interstellar and intergalactic space, the produced gamma rays have an intensity

$$I_\gamma(E_\gamma) = \int_0^L dr \int_{E_\gamma}^\infty I_e(E, \mathbf{r})\, dE \int_0^\infty d\varepsilon\, n_{\text{ph}}(\varepsilon, \mathbf{r})\, \sigma(E_\gamma, \varepsilon, E), \quad (3.22)$$

where $n_{\text{ph}}(\epsilon, \mathbf{r})d\epsilon$ —density of thermal photons with energies in the interval $d\epsilon$ at a point $\mathbf{r}$ in space, and $\sigma(E_\gamma, \epsilon, E)dE_\gamma$ —effective cross section for the production of a gamma quantum with an energy in the interval dE_γ when a photon of energy ϵ is scattered by an electron with a total energy E. The distributions over the directions of the thermal photons and electrons are assumed to be isotropic, and therefore $\sigma(E_\gamma, \epsilon, E)$ in (3.22) is an average over the angle between the directions of motion of the electron and the photon.

This cross section was calculated in [16]. Inasmuch as the calculation of the intensity (3.22), based on the exact value of the cross section $\sigma(E_\gamma, \epsilon, E)$ leads only to the appearance of a factor that is close to unity compared with the approximate derivation, we confine ourselves here to the latter (see also [52], in which attention was paid to the importance of allowing for the Compton gamma rays).

For the electron energy of interest to us, the condition $E < (mc^2)^2/4\epsilon \sim 5 \times 10^{10}$ eV is satisfied (average thermal-proton energy $\epsilon \sim 1$ eV), so that the total cross section of the Compton effect is equal to the Thomson cross section $\sigma_T = 8\pi r_0^2/3 = 6.65 \times 10^{-25}$ cm^2. In the isotropic case there is produced in the mean, during each scattering, a gamma quantum of energy (see [53] and also [16])

$$E_\gamma = \frac{4}{3}\bar{\varepsilon}\left(\frac{E}{mc^2}\right)^2, \quad (3.23)$$

where $\bar{\epsilon}$ —average energy of thermal photons.*

We can therefore use for the cross section $\sigma(E_\gamma, \bar{\epsilon}, E)$ averaged over the thermal-photon spectrum the approximate expression

$$\sigma(E_\gamma, \bar{\varepsilon}, E) = \frac{1}{n_{\text{ph}}}\int_0^\infty n_{\text{ph}}(\varepsilon)\,\sigma(E_\gamma, \varepsilon, E)\, d\varepsilon \quad (3.24)$$

$$= \sigma_T \delta\left(E_\gamma - \frac{4}{3}\bar{\varepsilon}\left(\frac{E}{mc^2}\right)^2\right),$$

where

$$n_{\text{ph}} = \int_0^\infty n_{\text{ph}}(\varepsilon)\, d\varepsilon$$

is the photon concentration. Substituting this expression in (3.22) and assuming that the photon concentration n_{ph} and the electron intensity $I_e(E)$ do not depend on the distance along the line of sight, we obtain

$$I_\gamma(E_\gamma) = \frac{\sqrt{3}}{4}\frac{N_{\text{ph}}(L)\,\sigma_T mc^2}{\sqrt{\bar{\varepsilon}E_\gamma}} I_e\left(mc^2\sqrt{\frac{3E_\gamma}{4\bar{\varepsilon}}}\right)$$

$$= \frac{N_{\text{ph}}(L)\,\sigma_T}{2}(mc^2)^{1-\gamma}\left(\frac{4}{3}\bar{\varepsilon}\right)^{\frac{\gamma-1}{2}} K_e E_\gamma^{-\frac{\gamma+1}{2}}, \quad (3.25)$$

where the electron spectrum is assumed in the last expression to obey a power-law form $I_e(E) = K_e E^{-\gamma}$. An exact calculation for a power-law spectrum of this type, produces in (3.25) an additional factor [16]

$$f(\gamma) = 4{,}74\,(1.05)^\gamma \frac{\gamma^2+4\gamma+1}{(\gamma+1)(\gamma+3)^2(\gamma+5)}\Gamma\left(\frac{\gamma+5}{2}\right)\zeta\left(\frac{\gamma+5}{2}\right), \quad (3.26)$$

where $\Gamma(x)$ is the Euler gamma function and $\zeta(x)$ is the Riemann function ($\zeta(x) = \sum_{n=1}^\infty n^{-x}$). The coefficient $f(\gamma)$ is equal to 0.84, 0.86, 0.99, and 1.4 for $\gamma = 1, 2, 3$, and 4 respectively.

Taking for the average radiation temperature of the stars $T = 5000$°K and consequently $\bar{\epsilon} = 2.7\,kT \simeq 1.2$ eV, and measuring E_γ in BeV, $w_{\text{ph}} = n_{\text{ph}}\bar{\epsilon}$ in eV/cm^3, and K_e in (BeV)$^{\gamma-1}$/cm^2-sec-sr [see (2.7)], we obtain from (3.25)

*The correctness of (3.23) can also be easily verified by using the expression for the Compton energy loss of the electron, namely $-(dE/dt)_c = cn_{\text{ph}}\,\sigma_T(4/3)\,\bar{\epsilon}\,(E/mc^2)^2 = (32\pi/9)\,(e^2/mc^2)^2 \times cw_{\text{ph}}\,(E/mc^2)^2$, and allowing for the fact that $cn_{\text{ph}}\sigma_T$ is the average frequency of electron-photon collisions. We note also the following. The condition $E \ll (mc^2)^2/\epsilon$ signifies that in the electron rest frame the photon has an energy $\epsilon' \sim \epsilon E/mc^2 \ll mc^2$. This is precisely why we can regard the scattering of light classically and use the Thomson cross section employed. In this approximation the effects exerted on the electron by the field of the electromagnetic wave and by the static magnetic field are very much the same. In particular, the Compton loss $-(dE/dt)_c$ indicated above differs from the cyclotron-radiation loss $-(dE/dt)_{cyc} = (2/3)\,(e^2/mc^2)^2 cH_\perp^2(E/mc^2)^2$ in that the energy density w_{ph} of the isotropic radiation is replaced by the average energy density of the isotropic magnetic field $H^2/8\pi = (3/2)\,(H_\perp^2/8\pi)$.

$$I_\gamma(E_\gamma)=2.8\cdot10^{-25}(7.9\cdot10^{-2})^{\gamma-1}f(\gamma)Lw_{\text{ph}}K_eE_\gamma^{-\frac{\gamma+1}{2}}\ \frac{\text{photons}}{\text{cm}^2\,\text{sec}\cdot\text{sr}\cdot\text{BeV}}. \quad (3.27)$$

The photon concentration is assumed here constant over the entire path L, and therefore $N_{\text{ph}}(L)\bar{\epsilon} = Ln_{\text{ph}}\bar{\epsilon} = Lw_{\text{ph}}$.

For the spectrum (2.7) we obtain from (3.27)

$$I_\gamma(>E_\gamma)=2\cdot10^{-28}Lw_{\text{ph}}E_\gamma^{-1/2}\ \frac{\text{photons}}{\text{cm}^2\,\text{sec}\cdot\text{sr}}, \quad (3.28)$$

where the energy E_γ is in BeV.

The spectrum (2.7) pertains only to the energy interval $0.5 < E < 10$ BeV. Inasmuch as by virtue of (3.23) the average energy of the gamma quanta produced by electrons with energy E is equal to $E_\gamma = 1.6\,(E/mc^2)^2$ eV for $\bar{\epsilon} = 1.2$ eV, the spectrum (3.28) holds, strictly speaking, for the region

$$10^6 \leqslant E_\gamma \leqslant 6\cdot10^8 \text{ eV} \quad (3.29)$$

However, up to $E_\gamma \simeq 2$—3 BeV, the inaccuracy in $I_\gamma(>E_\gamma)$, due to the inaccuracy of the spectrum (2.7) at high energies, is still low.

At even higher energies ($E_\gamma > 3$ BeV), the spectrum (3.28) becomes unsuitable not so much because of the change in the electron spectrum, but principally as a result of the arising energy dependence of the Compton cross section, which leads (if $E > (mc^2)^2/4\epsilon \sim 5\times10^{10}$ eV) to a rapid decrease in the total cross section. An approximate expression for $I_\gamma(E_\gamma)$ at energies $E_\gamma \sim E \gg 5\times10^{10}$ eV is given in [16].

3.4. Positron Annihilation

The annihilation of fast positrons ($E \gg mc^2$) has a cross section*

$$\sigma_{\text{an}}(E_\gamma, E) \approx \pi r_0^2\frac{mc^2}{E}\left(\ln\frac{2E}{mc^2}-1\right)\delta(E_\gamma-E), \quad (3.30)$$

where account is taken of the fact that one of the annihilation photons acquires an energy $E_\gamma \simeq E$. Therefore, according to (1.2) and (3.30)

$$I_{\gamma,\text{an}}(E_\gamma)=N(L)\,\sigma_{\text{an}}I_{e^+}(E_\gamma)$$
$$\approx 0.1M(L)\frac{mc^2}{E_\gamma}\left\{\ln\frac{2E_\gamma}{mc^2}-1\right\}I_{e^+}(E_\gamma). \quad (3.31)$$

By N(L) we must mean here the number of electrons in interstellar space, which, for an interstellar medium consisting mostly of hydrogen, is approximately equal to the number of atoms; therefore $N(L) = M(L)/2\times10^{-24}$. A maximum estimate for the intensity $I_{\gamma,\text{an}}$ can be obtained by assuming that the entire electronic component is secondary, that is, [see (2.7)]

$$I_{e^+}(E)\simeq\frac{1}{2}I_e(E)\simeq3\cdot10^{-3}E^{-2}.$$

In this case the intensity of the high-energy annihilation gamma quanta is equal to

$$I_{\gamma,\text{an}}(E)\simeq1.5\cdot10^{-7}M(L)\left(\ln\frac{2E_\gamma}{mc^2}-1\right)E_\gamma^{-3}, \quad (3.32)$$

where E_γ is measured in BeV. The intensity (3.32) is lower than the bremsstrahlung intensity (3.20) by a factor

$$\frac{5\cdot10^2E_\gamma}{\ln\frac{2E_\gamma}{mc^2}-1} \quad (3.33)$$

that is, it does not exceed the bremsstrahlung by 20% even when $E_\gamma = 5\times10^{-2}$ BeV.

Of great interest is the annihilation gamma radiation of stopping positrons, an experimental observation of which would yield an estimate of the intensity of the cosmic rays and concentration of interstellar gas in the far past [44], and of the rate of escape of cosmic rays from the galaxy.

The number of slow positrons annihilating per unit time and per unit volume is [54]

$$\nu n_{e^+}=n(\sigma v)_{v\to0}n_{e^+}=n\pi r_0^2cn_{e^+}, \quad (3.34)$$

where n —electron concentration, which for the interstellar medium is practically equal to the concentration of the gas atoms, $\pi r_0^2 = 3\sigma_T/8 = 2.5\times10^{-25}$ cm^2, and n_{e+} —concentration of slow positrons, which we assume to be the same at all points in the volume V of the galaxy.

For the galactic volume as a whole we have

$$\bar{\nu}Vn_{e^+}=\pi r_0^2c\,(n_{\text{disc}}V_{\text{disc}}+n_{\text{halo}}V_{\text{halo}})\,n_{e^+}=\pi r_0^2cV\bar{n}n_{e^+}, \quad (3.35)$$

where $\bar{n} = (n_{\text{disc}}V_{\text{disc}} + n_{\text{halo}}V_{\text{halo}})/V$ —average gas concentration in the galaxy, n_{disc} and n_{halo} —gas concentrations in the disc and in the halo, and V_{disc} and V_{halo} —their respective volumes.

By virtue of (3.35), the average lifetime of the slow positrons in the galaxy is

$$t_{\text{an}}=\frac{1}{\bar{\nu}}=\frac{1}{\pi r_0^2c\bar{n}}\simeq\frac{4\cdot10^6}{\bar{n}}\ \text{years}. \quad (3.36)$$

The average concentration of the electrons in the galaxy is $\bar{n}\sim10^{-2}$, and consequently $t_{\text{an}}\sim4\times10^8$ years.

At the same time it is clear from (3.35) that a considerable fraction of the positrons is annihilated in the disc, inasmuch as the mass of the gas in the disc (meaning also the total number of electrons in the disc, $n_{\text{disc}}V_{\text{disc}}$) amounts to not less than half, and is more likely to be the bulk of the entire gas in the galaxy. The latter circumstance should lead to a sufficiently sharp anisotropy of the annihilation radiation with a maximum in the direction of the galactic center.

The delay time of the positrons produced by nuclear collisions is determined primarily by the ionization losses [32]

*We consider here only two-photon annihilation, since its probability is much larger than that of one-photon and three-photon annihilation.[54]

$$-\left(\frac{dE}{dt}\right)_i = 7.62\cdot 10^{-9}\left\{3\ln\frac{E}{mc^2}+18.8\right\} n\,\frac{\text{eV}}{\text{sec}}. \quad (3.37)$$

For the main part of the secondary positrons [38] with energies on the order of 30—100 MeV, the time of ionization deceleration, at an average gas concentration $n \sim 10^{-2}$ cm^{-3}, is $T_i \simeq 4\times 10^8$—1.2×10^9 years. Thus, the time elapsed from the instant of formation of positrons to their annihilation in the galaxy, is $T \sim 8\times 10^8$—1.6×10^9 years.

If the diffusion escape of relativistic particles from the galaxy were to be small ("closed" model with diffusion escape time $T_{es} \gg T$), then the intensity of the annihilation radiation would be determined under stationary conditions simply by the number of electrons produced per unit time in nuclear collisions and in the decay of the produced mesons. Namely, in this case we would have

$$I_{\gamma,\,\text{an}}(E = 0.51\,\text{MeV}) = 2Q_e(L), \quad (3.38)$$

where

$$Q_e(L) = \int_0^L \frac{\tilde{q}_e}{4\pi}\,dr$$

is the number of positrons in a unit solid angle, produced in a unit time along the line of sight. Inasmuch as in the region of low energies, which make the main contribution to (3.38), the secondary electron-positron component consists practically entirely of positrons*, we can use for $Q_e(L)$ the value [38,16] $Q_e(L) = 0.44\,M(L)/\lambda$, which pertains to the total number of secondary electrons and positrons (here $\lambda \simeq 180$ g/cm^2 —absorption range of the cosmic rays in the interstellar gas).

Account is taken in (3.38) of the fact that two gamma quanta are produced in each annihilation act, and that in addition the generation of secondary positrons and electrons and the annihilation of positrons occur in the same regions of space, since both processes are proportional to the gas concentration.

Substituting the numerical values in (3.38) we obtain for the closed model

$$I_{\gamma,\,\text{an}}(0.51\,\text{MeV}) = 5\cdot 10^{-3} M(L)\,\frac{\text{photons}}{\text{cm}^2\,\text{sec}\cdot\text{sr}}. \quad (3.39)$$

Actually, however, the time T_{es} of diffusion escape of the fast particles from the galaxy amounts apparently to approximately 1—3×10^8 years [32], that is, approximately one order of magnitude less than the time T estimated above for the deceleration and annihilation of the positrons. Therefore, allowing for escape, the expression (3.39) will contain a small factor $\exp(-T/T_{es})$, which takes into account the fraction of the positrons retained in the galaxy during the deceleration time. This factor is strongly dependent on the times T_{es} and T, reaching a value 10^{-5} for $T_{es} = 10^8$ years and $T = 1.2\times 10^9$ years. Thus, in the case of rapid escape of the particles from the galaxy, the ionization losses cannot ensure the appearance of any appreciable number of slow positrons. We shall therefore consider other possibilities.

In the positron energy range of interest to us, $E \sim 30$—100 MeV, the average radiation and Compton energy losses are small compared with the collision losses (ionization losses). At the same time, in view of the "catastrophic" character of the radiation losses, there exists a finite probability of transferring to the photon almost the entire initial electron (positron) energy in a single collision. However, this probability is low. For example, for positrons with energy $E \sim 50$ MeV the probability per unit radiation length (equal to 66 g/cm^2 for hydrogen) of emitting a photon that carries away more than 90% of the initial energy is merely 3×10^{-2}*. The energy $E \lesssim 5$ MeV still retained is expended by the positron on collisions (ionization) within a time $T_{es} \simeq 10^8$ years. Inasmuch as the relativistic particle traverses in a time $T_{es} \simeq 10^8$ years through $x = \rho c T_{es} \simeq 2$ g/cm^2 of matter, which amounts to approximately $1/30$ of the radiation length in hydrogen, the fraction of positrons that slow down as a result of catastrophic radiation losses is $3\times 10^{-2}/30 \simeq 10^{-3}$. Thus, for small values of T_{es} this process is more effective than pure ionization deceleration.

At the same time, an even more important fact is that 0.5% of all the produced secondary positrons, approximately have an energy $\lesssim 5$ MeV (see the calculations in [38]). These positrons have time to decelerate within $T_{es} \simeq 10^8$ years, and therefore even if all the positrons with higher energy escape, the lower limit of the intensity of the annihilation gamma quanta amounts to

$$I_{\gamma,\,\text{an}}(0.51\,\text{MeV}) \simeq 2\cdot 10^{-5} M(L)\,\frac{\text{photons}}{\text{cm}^2\,\text{sec}\cdot\text{sr}}. \quad (3.40)$$

It is clear from the foregoing that the experimental determination of the value or of the upper limit of $I_{\gamma,\text{an}}$ (0.51 MeV) can serve as a very sensitive method for estimating the values of T_{es}, and also the intensity of cosmic rays and the mass of the gas in the galaxy in the remote past.

It must be borne in mind that gamma rays with energy $E_\gamma \sim 0.5$ MeV are produced also by other processes. It is consequently important to separate the narrow line $E_\gamma \simeq 0.51$ MeV, the width of which is determined in practice only by the thermal velocities of the positrons, since most positrons slow down before becoming annihilated [54].

*This is connected with the law of charge conservation: the generating component is positively charged.

*For estimating purposes one should use the expression for the probability of radiation deceleration in the absence of screening [49,50], which corresponds to the case of interest to us, that of relatively low initial energy and large fraction of energy transferred to the photon.

3.5. Nuclear Gamma Rays

The gamma radiation produced by the de-excitation of the excited nuclei can be due either to nuclei contained in the cosmic rays or to the "stationary" nuclei of the interstellar gas. In the former case the radiation has a continuous spectrum, which reflects the energy spectrum of the cosmic rays, the principal role being played by the interactions between medium and heavy cosmic-ray nuclei and the interstellar hydrogen. In the latter case the spectrum is discrete (it consists of rather narrow lines), and the intensity is determined principally by the number of collisions between sufficiently fast protons and the complex nuclei contained in the interstellar gas. An important role can be played here also by the subcosmic rays, whose energy is sufficient to excite nuclear levels. We are referring, obviously, to nuclear levels and corresponding gamma radiation with energy on the order of hundreds of keV or several MeV. The intensity of the discrete gamma radiation in this section of the spectrum can be roughly estimated by assuming that each collision between a fast proton and an interstellar-gas nucleus excites this nucleus or its fragments and is accompanied by the emission of one gamma quantum having an energy in the indicated interval. It is necessary to take into account here only nuclei having the levels of interest to us and at the same time present in the interstellar gas in noticeable amounts. We assume these to be the nuclei with $Z \geq 6$, which constitute about 0.1% of the composition of the interstellar gas. Assuming therefore that the number of such nuclei along the line of sight is $N_{\mathrm{nuc}}(L) = 10^{-3}N(L)$, we obtain for the intensity

$$I_{\gamma,\,\mathrm{nuc}} \simeq 10^{-3} N(L)\, \sigma I_{\mathrm{c.r.}}, \qquad (3.41)$$

where $\sigma \simeq 3 \times 10^{-25}\ \mathrm{cm}^2$ is the cross section for the interactions of the nuclei from the group C, N, O (the role of the heavier elements is, generally speaking, slight) with the cosmic protons, and $I_{\mathrm{c.r.}} \approx 0.20$ protons/cm^{2}sec-sr is the total intensity of the protons contained in the cosmic rays (in view of the approximate character of the estimate, we neglect the contribution of the heavier nuclei). Substituting these values in (3.41) we obtain

$$I_{\gamma,\,\mathrm{nuc}} \simeq 6\cdot 10^{-29} N(L) \simeq 3\cdot 10^{-5} M(L) \frac{\text{photons}}{\mathrm{cm}^2\ \mathrm{sec}\cdot\mathrm{sr}}\ . \qquad (3.42)$$

We see that this intensity is comparable with the miniimum intensity of the annihilation gamma quanta (3.40). Yet it is important to note, as already emphasized, that the annihilation radiation is concentrated in a rather narrow section of the spectrum near $E_\gamma = 0.51$ MeV, whereas the intensity (3.42) pertains to gamma rays produced at once in all the nuclear lines of the elements contained in the interstellar gas.

We can estimate analogously the spectral intensity of the gamma rays produced upon excitation of the nuclei contained in cosmic rays, as a result of collisions with interstellar hydrogen. In this case the fraction of nuclei of interest to us is $\sim 1\%$ of the total intensity of the cosmic rays with given energy per nucleon E_n, that is, $I_{\mathrm{nuc}}(E_n) \sim 10^{-2} I(E_n)$. The gamma-quantum energy is connected with the total energy $E = AE_n$ of the excited nucleus by the relativistic transformation

$$E_\gamma \simeq E_\gamma^0 \frac{E}{Mc^2} = E_\gamma^0 \frac{E_n}{M_p c^2}\,, \qquad (3.43)$$

where E_γ^0—energy of the gamma quantum in the rest frame of the excited nucleus with mass M. As a result we have

$$I_{\gamma,\mathrm{nuc}}(E_\gamma)\, dE_\gamma = \sigma_{\mathrm{nuc}} N(L)\, 10^{-2} I(E)\, dE$$
$$= 10^{-2}\sigma_{\mathrm{nuc}} N(L)\, I\left(Mc^2 \frac{E_\gamma}{E_\gamma^0}\right) \frac{Mc^2}{E_\gamma^0}\, dE_\gamma \qquad (3.44)$$

or for the spectrum (2.1)

$$I_{\gamma,\mathrm{nuc}}(E_\gamma) \simeq 4\cdot 10^{-27} N(L) \left(\frac{Mc^2}{E_\gamma^0}\right)^{-1.6} E_\gamma^{-2.6}. \qquad (3.45)$$

Assuming that $E_\gamma^0 \sim 1$ MeV, we get

$$I_{\gamma,\mathrm{nuc}}(E_\gamma) \sim 6\cdot 10^{-32} N(L)\, E_\gamma^{-2.6} \simeq 3\cdot 10^{-8} M(L)\, E_\gamma^{-2.6},$$
$$I_{\gamma,\mathrm{nuc}}(>E_\gamma) \sim 2\cdot 10^{-8} M(L)\, E_\gamma^{-1.6}, \qquad (3.46)$$

where E_γ is measured in BeV.

The intensity of the nuclear gamma rays (3.46) in the high-energy region $E_\gamma > 5 \times 10^7$ eV is negligibly small compared with the intensity of the gamma radiation due to π^0-meson decay.

3.6. Absorption of Gamma and X Rays

In calculating the radiation intensity we have assumed that the radiation propagates in the interstellar or metagalactic space without any absorption. Fortunately, this assumption corresponds to reality in the overwhelming majority of cases that can be discussed at present. A brief discussion of absorption is nonetheless necessary.

Gamma ray absorption results essentially from three processes: electron-positron pair production, Compton scattering*, and photoeffect[50,54].

At gamma ray energies $E_\gamma > 10^8$ eV, absorption is due to pair production. We note that the pairs are produced from both nuclei and electrons. In addition, it is quite natural for absorption in a neutral gas to differ somewhat from that in an ionized gas. In a neutral gas, at high energies ($E > 10^8$ eV) pair production can be assumed in first approximation to occur under total screening conditions, the absorption coefficient in atomic hydrogen being

$$\mu = 1.2\cdot 10^{-2}\,\mathrm{cm}^2/\mathrm{g} = 2\cdot 10^{-26}\, n\ \mathrm{cm}^{-1}. \qquad (3.47)$$

*In Compton scattering, of course, the gamma photon does not vanish but is converted into a different photon. Here, however, we mean by absorption just the total attenuation of the flux of gamma rays in question, regardless of whether this is due to true absorption or scattering.

We take account here of the fact that the "cascade length unit" in hydrogen is 66 g/cm^2, and a path equal to 1 g/cm^2 of hydrogen corresponds to a distance equal to $6 \times 10^{23}/n$ centimeters (n —hydrogen atom concentration).

In an ionized gas screening can always be neglected under the conditions in the interstellar medium, and for a hydrogen plasma we have

$$\mu = 3.6 \cdot 10^{-27} \left(\ln \frac{E_\gamma}{mc^2} - 1.9 \right) n \text{ cm}^{-1}$$
$$= 2.1 \cdot 10^{-3} \left(\ln \frac{E_\gamma}{mc^2} - 1.9 \right) \text{ cm}^2/\text{g}. \quad (3.48)$$

If we assume that the interstellar medium contains about 10% helium and less than 1% of heavier elements, the absorption coefficient μ is increased by approximately 20%. The accuracy with which the gas density is known under cosmic conditions is even lower, so that such a correction is insignificant, and we are justified in using (3.47) and (3.48). We note that these expressions coincide approximately when $E_\gamma \simeq 10^9$ eV, so that in most cases we can confine ourselves to (3.47).

In accordance with the definition of the absorption coefficient, the gamma ray intensity decreases along a path L like

$$I = I_0 e^{-\mu L} = I_0 e^{-\tau}.$$

If the coefficient μ is given in cm^2/g, then L must be in g/cm^2, that is, we must use the quantity M(L) introduced in Sec. 2. As indicated in Table I, M(L) $= 6 \times 10^{-2}$ g/cm^2 in the galaxy even in the direction of the center, and therefore, in accordance with (3.47), absorption changes the gamma-ray intensity by an amount characterized by a factor $e^{-\tau} \simeq (1 - \tau)$, where $\tau = \mu M(L) \simeq 7.2 \times 10^{-4}$. For the metagalaxy M(L) $= 0.1$ g/cm^2 and $\mu M(L) \simeq 1.2 \times 10^{-3}$. Thus, the absorption of high-energy gamma rays in the galaxy and metagalaxy can be neglected. To be sure, it is still necessary to consider separately the absorption connected with the production of electron-positron pairs by gamma rays interacting with thermal photons [55]. This mechanism is in operation when $E_\gamma \gtrsim 10^{11}$ eV and is most effective under cosmic conditions (the thermal-photon energy is $E \sim 1$ eV) when $E_\gamma \simeq 10^{12}$ eV.

It can be shown [32] that in the galaxy we have for this process $\mu_{max} L < 10^{-2}$. In the metagalaxy, at a photometric distance $R_{ph} \simeq 5 \times 10^{27}$ cm, the maximum absorption is $\mu_{max} R_{ph} \sim 1$, but along the path from the majority of radio galaxies, the absorption is already small. We note that for gamma rays with energy $E_\gamma \gtrsim 10^{18}$ eV it would be necessary to take into account [56] the absorption connected with pair production on photons in the radio band.

For gamma rays with energy $E_\gamma < 10^8$ eV, it is important to take into account the Compton scattering, and for $E_\gamma < 50$ keV, the photoeffect can also be significant. The cross section for the scattering is smaller than or equal to the Thomson cross section σ_T. The coefficient μ connected with the Compton scattering does not exceed

$$\mu_K = \sigma_T n = 6.65 \cdot 10^{-25} n \text{ cm}^{-1} = 0.4 \text{ cm}^2/\text{g}. \quad (3.49)$$

Consequently in the galaxy and metagalaxy $\tau = \mu_C M(L) \lesssim 0.04$, and the absorption is small, as before.

The low-energy region ($E_\gamma < 50$ keV) will be called the x-ray region. Now the chemical composition of the gas and the degree of ionization become important factors. We shall not dwell on this question in detail. According to [57], for $E_\gamma = 4$ keV ($\lambda = 3$ Å) in the interstellar medium $\tau = \mu L \simeq 7 \times 10^{-24} M(L)$, that is, $\tau \simeq 0.2$ even for $N(L) = 3 \times 10^{22}$ (in the direction of the galactic center). For $E_\gamma = 1.5$ keV ($\lambda = 8$ Å), the absorption is already approximately 5 times larger and can therefore become significant for the metagalaxy and for sources located far from the solar system in the direction of the galactic center. However, even in the direction of the anticenter (let alone the pole) $\tau(\lambda = 8 \text{ Å}) \simeq 3.3 \times 10^{-23} N(L) \simeq 0.2$.

4. COSMIC GAMMA RADIATION (DISCUSSION)

4.1. Intensity of Over-all Cosmic Gamma Radiation

If we refer to high-energy gamma rays ($E_\gamma \gtrsim 50$ MeV), then the decisive role is played by their production as a result of π^0-meson decay, bremsstrahlung, and Compton scattering. The corresponding intensities for the galaxy, as shown in Sec. 3, are

$$I_{\gamma,\pi^0}(> E_\gamma) = 3 \cdot 10^{-4} M(L) E_\gamma^{-1.8} (1 \leqslant E_\gamma \leqslant 10^6 \text{BeV}), \quad (4.1)$$
$$I_{\gamma,\text{br}}(> E_\gamma) = 8 \cdot 10^{-5} M(L) E_\gamma^{-1} (1 \leqslant E_\gamma \leqslant 10 \text{BeV}), \quad (4.2)$$
$$I_{\gamma,\text{compt}}(> E_\gamma) = 2 \cdot 10^{-28} L w_{ph} E_\gamma^{-1/2} (10^{-3} \leqslant E_\gamma \leqslant 3 \text{BeV}), \quad (4.3)$$

where $I_\gamma(> E_\gamma)$ is measured in photons/cm^{2}sec-sr, E_γ is in BeV, and the thermal radiation energy density w_{ph} is in eV/cm^3.

In Table II are given values of the intensity $I_\gamma(> E_\gamma)$, calculated from formulas (4.1)—(4.3) for $E_\gamma = 1$ BeV. It also lists the intensities for $E_\gamma = 50$ MeV. For this case, we used in calculating $I_{\gamma,\pi^0}(E_\gamma > 50$ MeV) the value (3.8) for the total number of produced π^0 mesons, hence

$$I_\gamma(> 50 \text{MeV}) = 4.8 \cdot 10^{-3} M(L), \quad (4.4)$$

and $I_{\gamma,br}(> 50$ MeV) was estimated by means of formula (4.2) under the assumption that the electron spectrum (2.7) remains valid up to electron energies $E \sim 50$ MeV (this gives an upper estimate for the bremsstrahlung intensity, inasmuch as in the region of low energies the electron spectrum probably becomes more gently sloping or passes through a maximum; however, there are no reliable data whatever on the electron spectrum in the region $E < 0.5$ BeV). As to the Compton gamma rays, formula (4.3) can be used without stipulation, since it pertains to the energy interval $1 \lesssim E_\gamma \lesssim 3$ BeV. The values of L, M(L), and w_{ph}

Table II. Intensity of gamma radiation $I_\gamma(>E_\gamma)$, in cm^{-2} sec^{-1} sr^{-1}

Process	E_γ	Galactic radiation				Metagalaxy
		towards			Averaged directionally	
		center	anticenter	pole		
1. $\pi^\circ \to \gamma+\gamma$ . .	1 BeV	$2\cdot10^{-5}$	$4\cdot10^{-6}$	$2\cdot10^{-7}$	$5\cdot10^{-7}$	$3\cdot10^{-4}\ \xi_{c.r.}$
2. Bremsstrahlung		$5\cdot10^{-6}$	10^{-6}	$5\cdot10^{-8}$	$1.3\cdot10^{-7}$	$8\cdot10^{-6}\ \xi_e$
3. Compton effect		$3\cdot10^{-6}$	$6\cdot10^{-7}$	$3\cdot10^{-6}$	$3\cdot10^{-6}$	$2\cdot10^{-3}\ \xi_e$
1. $\pi^\circ \to \gamma+\gamma$ . .	50 MeV	$3\cdot10^{-4}$	$6\cdot10^{-5}$	$3\cdot10^{-6}$	$8\cdot10^{-6}$	$5\cdot10^{-4}\ \xi_{c.r.}$
2. Bremsstrahlung		10^{-4}	$2\cdot10^{-5}$	10^{-6}	$3\cdot10^{-6}$	$1,6\cdot10^{-4}\ \xi_e$
3. Compton effect		$1,3\cdot10^{-5}$	$3\cdot10^{-6}$	$1,3\cdot10^{-5}$	$1.3\cdot10^{-5}$	$9\cdot10^{-3}\ \xi_e$

used to calculate $I_\gamma(>E_\gamma)$ were taken from Table I.

As can be seen from Table II, the pion and bremsstrahlung gamma rays produced in the galaxy are characterized by a rather sharp anisotropy, with a maximum in the direction of the galactic center. The Compton gamma rays, to the contrary, have an almost isotropic distribution, and they make the main contribution to the directionally-averaged intensity of the galactic gamma radiation.*

Table II lists also the expected values of the gamma ray intensity from the metagalaxy. The assumed values of L, M(L) and w_{ph} were discussed in Sec. 2 (see Table I), and the factors $\xi_{c.r.}$ and ξ_e take into account the differences between the intensities of the cosmic rays and the relativistic electrons in the metagalaxy and their galactic values [see formula (2.4), and analogously for $I_e(E)$].

It is clear from Table II that the intensity of the metagalactic gamma rays already exceeds the directionally-averaged intensity of the gamma rays produced in the galaxy when $\xi_{c.r.} > 2\times10^{-2}$ or $\xi_e > 1.5\times10^{-3}$, that is, when the intensity of the cosmic rays and the intensity of the electrons in the metagalaxy exceed 2 and 0.15% of their galactic values, respectively. In the case when $\xi_{c.r.} \gtrsim 1$ or $\xi_e \gtrsim 3\times10^{-2}$, the metagalactic gamma radiation exceeds the galactic radiation even in the direction of the center, and the gamma-ray anisotropy associated with the galaxy is greatly reduced. Thus, measurements of the intensity of the gamma rays and of its dependence on the direction make it possible in principle to separate (or to establish an upper bound for) the intensity of the gamma rays from the metagalaxy, and yield by the same token valuable information on the cosmic rays in the metagalaxy and their electronic component.

*We note that Table II of our paper [16], which is similar to Table II of the present article, lists somewhat different values for the intensity of the bremsstrahlung and Compton gamma rays. The reason is that we use in the present article one-fourth the value of the electronic component and the density w_{ph} for the halo has been reduced one-half.

We have already seen that in the energy region in question the contribution of the annihilation (3.33) and nuclear (3.36) gamma rays is negligibly small compared with the intensities (4.1)–(4.3).

Let us dwell now on gamma rays with very high energy, $E_\gamma > 10^{11}$ eV. At these energies the intensity of the Compton gamma rays is low, owing both to the decrease in the cross section (formula (4.3) is in this case already negligible) and to the increase in the exponent γ of the electron spectrum $I_e(E) = K_e E^{-\gamma}$ (apparently $\gamma \gtrsim 2.6$ when $E > 10$ BeV). The latter factor decreases also the role of the bremsstrahlung gamma rays. To the contrary, formula (4.1) for the gamma rays from the π^0-meson decay holds true up to energies $E_\gamma \sim 10^6$ BeV $\simeq 10^{15}$ eV (see Sec. 3.1). Since a kink corresponding to an increase in the slope of the spectrum is observed in the cosmic-ray spectrum at $E \sim 10^{16}$ eV (the exponent increases to a value $\gamma \simeq 3.1 \pm 0.1$), formula (4.1) no longer holds when $E \gtrsim 10^6$ BeV (this pertains primarily to the energy dependence, although it is not unlikely that at such high energies a change takes place in the π^0-meson production process itself).

At the same time, in the energy region $E_\gamma > 10^6$ eV an important role is assumed by the gamma quanta from the decay of π^0 mesons produced by collisions with thermal photons [12]. For the metagalaxy $N_{ph}(L) = n_{ph}L \approx 10^{25}$ (see Table I); therefore in the region $E_\gamma > 10^{16}$ eV the intensity of such photons amounts to approximately 10^{-5} of the intensity of cosmic rays having the same energy [see (3.16)]. At lower energies, the intensity of such gamma quanta decreases rapidly, in connection with the presence of an energy threshold in the process under consideration.

We note that the value assumed in [12] for the photon density in the metagalaxy was $n_{ph} \simeq 0.2$, and the value obtained for the gamma ray intensity was two orders of magnitude larger than that indicated by us ($I_\gamma \sim 10^{-5}I$). However, there are at present no grounds whatever for choosing this value of n_{ph} for the metagalaxy; a direct estimate yields $n_{ph} \simeq 2\times10^{-3}$ (see [32]).

Table III. Intensity $I_\gamma (E_\gamma \geq 0.5$ MeV) (in $cm^{-2} sec^{-1} sr^{-1}$)

Process	Gallactic radiation				Metagalaxy
	towards			Averaged directionally	
	center	anticenter	pole		
1. Positron annihillation	$(1.2-300) \times 10^{-6}$	$(2.4-600) \times 10^{-7}$	$(1.2-300) \times 10^{-8}$	$(3.2-800) \times 10^{-8}$	$\ll 5 \cdot 10^{-4}\ \xi_{c.r.}$ (without account of relict positrons)
2. Compton effect	$1.3 \cdot 10^{-4}$	$2.7 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$10^{-1}\ \xi_e$
3. Nuclear gamma rays	$2 \cdot 10^{-6}$	$4 \cdot 10^{-7}$	$2 \cdot 10^{-8}$	$5 \cdot 10^{-8}$	$3 \cdot 10^{-6}\ \xi_{c.r.}$

We note that even if we choose $n_{ph} \simeq 0.2$ and the same cosmic ray intensity $I(E)$ as in the galaxy,* the frequency estimated in [12] for the muon-poor extensive air showers due to primary photons (with account of the character of photon cascade development in the atmosphere) is approximately one order of magnitude lower than that obtained from observation [39,40]. The question of the nature of the showers containing a small number of muons and their connection with primary high-energy gamma rays is still far from clear (see in this connection, in particular, [16]), but by virtue of the foregoing it is highly improbable that they are due to gamma rays from the process considered for the production of π^0 mesons from thermal photons.

Of course, this conclusion does not contradict the fact, made clear by comparison of (3.13) with (3.16), that for the metagalaxy the intensity of the high-energy gamma rays from photomesons becomes equal to or even larger than the intensity of the gamma rays from the π^0 mesons due to nuclear collisions if $n \sim 10^{-5}$ and $n_{ph} \sim 2 \times 10^{-3}$. In the galaxy the total number of thermal photons along the line of sight is $N_{ph}(L) \sim w_{av}/\bar{\epsilon}_{ph})L \lesssim 3 \times 10^{22}$, that is, considerably lower than $N_{ph}(L)$ for the metagalaxy. Therefore, in accordance with (3.15), the intensity of the gamma rays produced by the decay of the π^0 mesons created by collisions between cosmic rays and thermal photons is $I_\gamma \sim 3 \times 10^{-8} I$. At the same time, according to (3.13), for $E \sim 10^7$ BeV the intensity of the gamma rays from the decay of the π^0 mesons produced in the gas, in the direction of the pole ($N(L) \simeq 3 \times 10^{20}$) is $I_{\gamma,\pi^0} = 6 \times 10^{-9} I$. In the direction of the center, however, we already have $I_{\gamma,\pi^0} = 6 \times 10^{-7} I$.

Of great interest is the region of low energies $E_\gamma \gtrsim 0.5$ MeV. Without touching upon the possible appreciable contribution made to this region by gamma rays due to subcosmic protons and electrons, we present only estimates of the intensity $I_\gamma (> 0.5$ MeV) for annihilation [see (3.39) and (3.40)], Compton [see (4.3)], and nuclear gamma rays [see (3.42)]. The corresponding values are listed in Table III.

In the first line of Table III the lower values of the annihilation gamma ray intensity (1.2×10^{-6}, 2.4×10^{-7}, 1.2×10^{-8}, 3.2×10^{-8}) were obtained from formula (3.40), which gives a lower intensity limit corresponding to a rapid escape of the positrons from the galaxy (it is precisely this assumption which appears to us to be the more probable [32]). The largest values indicated in the same line correspond to the case of slow escape of the cosmic rays, including positrons, from the galaxy [see (3.39)]. The value $I_\gamma (> 0.5$ MeV) $= 5 \times 10^{-4} \xi_{c.r.}$ (see the last column of Table III) would correspond to the case when all the positrons produced in the metagalaxy have time to annihilate rapidly. Actually this is not the case, since the time of positron slowing-down and annihilation in metagalactic space, at the contemporary gas concentration $n \lesssim 10^{-5}$ cm^{-3}, reaches 10^{12} years. Therefore the value $I_\gamma (> 0.5$ MeV) $= 5 \times 10^{-4} \xi_{c.r.}$ is highly exaggerated when referred to positrons produced in our own epoch. The true value of I_γ is determined by the concentration n_{e^+} of the slow positrons in metagalactic space [see (3.34)]:

$$I_\gamma(0.51 \text{ MeV}) = v \frac{n_{e^+} L}{4\pi} = 3 \cdot 10^7 n_{e^+}$$

for $L = R_{ph} = 5 \times 10^{27}$ cm and $n = 10^{-5}$ cm^{-3}. If we assume that $n_{e^+} \lesssim 3 \times 10^{-14}$ cm^{-3} (this corresponds to the concentration of the metagalactic electronic component of the cosmic rays; see Sec. 4.3), then I_γ (0.51 MeV) $\lesssim 10^{-6}$. The contemporary value of n_{e^+} is determined by processes occurring during that phase of the evolution of the metagalaxy, about which we know practically nothing.*

Thus, the estimate $I_\gamma (0.51$ MeV) $\ll 5 \times 10^{-4} \xi_{c.r.}$ for the annihilation gamma radiation is valid only if the concentration n_{e^+} of the slow relict positrons, that is, the positrons produced during early stages, is sufficiently small. It becomes clear by the same token that the experimental estimate of the intensity I_γ (0.51 MeV) or of its upper limit enable us to estimate or indicate an upper limit for the concentration of the slow positrons in metagalactic space.

As can be seen from Table III, the main contribu-

*Up to $E \approx 10^{17}$ eV the cosmic ray intensity in the metagalaxy is apparently smaller than in the galaxy.

*If we use the Einstein-de Sitter evolutional model, in which the concentration of the gas varies like $n(t) = n(T_{Mg}) (T_{Mg}/t)^2$, then ($t = T_{Mg} \approx 10^{10}$ years) the only positrons that have slowed down by the present instant of time are those produced at the instant $t = 2 \times 10^8$ years or before.

Table IV. Flux $F_\gamma (E_\gamma > 1$ BeV) (in cm^{-2} sec^{-1})

Source	R, cm	V, cm^3	M_V, g	w_{ph}, eV/cm^3	$W_{c.r.}$ erg	Process		
						π^0-meson decay	Bremsstrahlung	Compton effect
Crab nebula	$3.4 \cdot 10^{21}$	$6.6 \cdot 10^{55}$	$2 \cdot 10^{32}$	4	$5 \cdot 10^{48}$	$2 \cdot 10^{-10}$	$5 \cdot 10^{-11}$	$2 \cdot 10^{-10}$
M31 galaxy (Adromeda)	$2.2 \cdot 10^{24}$	$1.2 \cdot 10^{69}$	$6 \cdot 10^{42}$	1	$4 \cdot 10^{56}$	$8 \cdot 10^{-11}$	$2 \cdot 10^{-11}$	10^{-8}
Radio galaxy M87 (A-Virginis)	$3.4 \cdot 10^{25}$	$5 \cdot 10^{68}$	$3 \cdot 10^{42}$	1	10^{58}	10^{-11}	$3 \cdot 10^{-12}$	10^{-9}
Radio galaxy A-Cygni	$6.8 \cdot 10^{26}$	$2 \cdot 10^{69}$	$3 \cdot 10^{42}$	1	$3 \cdot 10^{60}$	$2 \cdot 10^{-12}$	$5 \cdot 10^{-13}$	10^{-9}

Remark. The flux $F_\gamma (E_\gamma > 50$ MeV) is approximately one order of magnitude larger than the presented values of $F_\gamma (E_\gamma > 1$ BeV). (see Table II). The data for the quasar 3C-273-B are listed in the text.

tion to the region of gamma-ray energy in question is made by the Compton scattering of the electrons by thermal photons. However, in the case of slow escape of the particles from the galaxy, annihilation gamma rays are also important, particularly if it is recognized that this radiation is concentrated in a rather narrow line. As to the nuclear gamma rays, in view of their low intensity, which is furthermore distributed over a broad spectral interval, detection of this radiation is a very complicated problem.

4.2. Gamma Radiation From Discrete Sources

The possible discrete gamma sources which we shall consider are the following characteristic objects*: supernova envelope—the Crab nebula, the normal galaxy M31 (large nebula in the Andromeda constellation), the radio galaxies A-Virginis and A-Cygni and also the quasar 3C-273. We shall consider only the three main gamma-radiation mechanisms: π^0-meson decay, bremsstrahlung, and Compton radiation. To estimate the expected gamma-ray flux $F_\gamma (> E_\gamma)$ it is necessary to replace M(L) in formulas such as (4.1) and (4.2) by the integral

$$\int \varrho(\mathbf{r})\, dr\, d\Omega \approx \frac{1}{R^2} \int \varrho(\mathbf{r})\, dV = \frac{M_V}{R^2},$$

where $\rho(\mathbf{r})$ —density and M_V —total mass of the gas in the source, R —distance to the source, and the integrals are taken over the volume V of the source [see (1.4)]. The product $w_{ph}L$ in (4.3) must accordingly be replaced by $w_{ph}V/R^2$. In addition, account must be taken of the fact that the intensity and spectrum of the cosmic rays and of their electronic component in the sources in question differ from their galactic values. Unfortunately, the intensity of the relativistic particles can be estimated for these remote sources only very approximately, using their radio emission data[32]. We shall assume that the cosmic-ray spectrum is characterized for all these sources by the same exponent γ as in the galaxy, and that the intensity is proportional to the cosmic-ray energy density $W_{c.r.}/V$. By $W_{c.r.}$ we mean here the total energy of the cosmic rays in the source, which is assumed to be 100 times larger than the total energy W_e of the electrons that cause the observed bremsstrahlung. Under these assumptions there appears in (4.1) an additional factor $W_{c.r.}/Vw_{c.r.G}$, while in formulas (4.2) and (4.3) there appears a factor $W_e/Vw_{e.G}$, where $w_{c.r.G} \approx 1$ eV/cm^3 —energy density of the cosmic ray in the galaxy, and $w_{e,G} \approx 10^{-2} w_{c.r.G}$ —energy density of their electronic component. Thus,

$$F_{\gamma,\pi^0}(> E_\gamma) = 3 \cdot 10^{-4} \frac{M_V W_{c.r.}}{R^2 V w_{c.r.,G}} E_\gamma^{-1.8} \frac{\text{photons}}{\text{cm}^2\text{sec}}, \quad (4.5)$$

$$F_{\gamma,\text{торм}}(> E_\gamma) = 8 \cdot 10^{-5} \frac{M_V}{R^2} \frac{W_e}{V w_{e,G}} E_\gamma^{-1} \frac{\text{photons}}{\text{cm}^2\text{sec}}, \quad (4.6)$$

$$F_{\gamma,\text{compt}}(> E_\gamma) = 2 \cdot 10^{-28} \frac{V w_{ph}}{R^2} \frac{W_e}{V w_{e,G}} E_\gamma^{-0.5} \frac{\text{photons}}{\text{cm}^2\text{sec}}. \quad (4.7)$$

The initial data and the results of the estimate of the gamma-ray flux, for the indicated processes and sources are listed in Table IV. The possible error is connected with the known arbitrariness in the choice of the value of $W_{c.r.}$, and also with the assumption that the cosmic rays, the gas, and the radiation fill uniformly the entire volume V of the source. Actually, the volume occupied by the cosmic rays may contain little gas, as is the case, for example, with the radio galaxy A-Cygni or for the jets in the radio galaxy A-Virginis. The least sensitive to this inhomogeneity is the Compton effect, which ensures the largest gamma-ray intensity.

The Compton effect should play a particularly large role in the case of quasars (objects of the type 3C-273-B, 3C-48, etc.), if the optical emission of these sources has a cyclotron-radiation nature (we are referring, of course, only to optical emission with a continuous spectrum). In fact[23], the dimensions of the quasar are relatively small, and its luminosity is tremendous. Therefore the radiation density is very large near the radiating surface and, in accordance with the

*The exploding galaxy M82 was considered from this point of view in [75] (no anomalously large values were obtained in this case for the flux of gamma and x-rays).

assumption on the cyclotron-radiation nature of the emission, the relativistic-electron concentration is large. The flux obtained in [23] for the quasar 3C-273-B is

$$F_\gamma(2.7\cdot 10^6 < E_\gamma < 10^8 \text{eV}) = 5\cdot 10^{-6}\frac{\text{photons}}{\text{cm}^2\text{sec}}.$$

The radius of the quasar was assumed to be $r = 2 \times 10^{16}$ cm, which leads to a value $w_{ph} = L/4\pi r^2 c = 5.4 \times 10^{13}$ eV/cm^3 ($L = 1.3 \times 10^{46}$ erg/sec —optical luminosity of the quasar 3C-273-B).

Actually the radius of the quasar can be one to three orders of magnitude larger than the value $r = 2 \times 10^{16}$ cm given above (the question of the value of r is still quite unclear). It can be shown that the gamma-ray flux calculated in accordance with the scheme of [23] is inversely proportional to the radius r of the radiating envelope and can therefore be one to three orders of magnitude smaller than the value $F_\gamma = 5 \times 10^{-6}$ photons/cm^2 sec given above.

Thus, the flux of gamma rays from the quasar need not necessarily be very large compared with the other cases (see Table IV). However, if the optical emission of the quasars is actually due to cyclotron radiation, then the gamma-ray flux from these objects may turn out to be sufficiently high to be observable.

4.3. Experimental Data, Their Evaluation, and a Few Conclusions

In accordance with the estimates of the expected intensity and the experimental registration capabilities, the primary gamma-radiation energy band can be subdivided into the following sections:

Region of low energies, $E_\gamma \simeq 0.1-10$ MeV. In this region, of greatest interest from the point of view of cosmic rays is the annihilation radiation of positrons and nuclear line emission. However, as is clear from Table III, the expected intensities of the gamma rays for these processes are quite small, and the lines may be masked by the continuous spectrum from the Compton gamma rays. In addition, the possible existence of a large number of subcosmic electrons must be borne in mind, and their bremsstrahlung could play a fundamental role in this energy interval.

Measurements of the gamma-ray intensity in this energy interval, made with rockets outside the atmosphere [6,59,60] yield a directionally-averaged value I_γ (> 0.3 MeV) $\simeq 3 \times 10^{-2}$ photon/cm^{2}sec-sr. This is more than two orders of magnitude larger than the maximum estimate for the galaxy given in Table III, and, if we disregard the possible contribution of solar gamma rays (see [61]), may be connected either with the metagalaxy or with the subcosmic particles (we disregard here, of course, the still unrefuted assumption that gamma rays of atmospheric origin played a role in the measurements of [5,59,60]).

Although the expected intensity of annihilation radiation of the stopped positrons is small, this radiation is concentrated in the narrow line $E_\gamma = 0.51$ MeV, the width of which is determined in practice only by the velocity of the atomic electrons and by the Doppler effect. This circumstance results in a gain of approximately 10^2 times compared with the continuous spectrum of the same intensity I_γ (> 0.5 MeV) (see Table III), if a receiver with high energy resolution is used.

Region of medium energies 50 MeV $\lesssim E_\gamma \lesssim$ 10 BeV. Starting with $E_\gamma \sim 50$ MeV, there should be observed, in addition to bremsstrahlung in Compton gamma rays from relativistic electrons, also gamma rays from the decay of π^0 mesons produced in nuclear interactions of cosmic rays. For this energy region, measurements [5] made outside the atmosphere on the "Explorer-XI" satellite, yielded an intensity value

$$I_\gamma(> 40\,\text{MeV}) = (3{,}3 \pm 1.3)\,10^{-4}\frac{\text{photons}}{\text{cm}^2\text{sec}\cdot\text{sr}}.$$

This value is more likely an upper limit, since a considerable unaccounted-for contribution may be due to gamma rays coming from the earth's atmosphere. Consequently, on the basis of the data of [5], we can assume that

$$I_\gamma(> 50\ \text{MeV}) \leqslant 3.3\cdot 10^{-4}\frac{\text{photons}}{\text{cm}^2\text{sec}\cdot\text{sr}}. \quad (4.8)$$

The intensity (4.8) is averaged over the directions of arrival of the gamma rays; the available data on the directional distribution still do not allow us to make any assumptions with respect to the presence of a real anisotropy.

As seen from Table I, the intensity (4.8) is more than one order of magnitude larger than the summary intensity expected for the galaxy from the three main processes in question. Therefore if we regard the value of (4.8) as actual (and not as an upper limit, which may be greatly reduced), then it is most probable that the observed radiation is connected with the metagalaxy. In this case we must assume either that the intensity of the cosmic rays in the metagalaxy is comparable with the galactic intensity (that is, $\xi_{c.r.} \simeq 1$ and simultaneously $\xi_e < 4 \times 10^{-2}$), or that for the relativistic electrons in the metagalaxy we have $\xi_e \simeq 4 \times 10^{-2}$ with $\xi_{c.r.} \ll 1$.

The first possibility encounters great difficulties and has low probability, particularly if we recognize that the assumed value of the gas concentration in the metagalaxy, $n \simeq 10^{-5}$, may be an overestimate. In this respect it is more probable that the intensity (4.8) is due to Compton scattering of relativistic electrons by thermal photons in the metagalaxy, and the intensity of such electrons is $\xi_e^{-1} \simeq 30$ times smaller than the galactic intensity. At any rate, the result of [5] leads to a very important conclusion: the intensity of the electronic component of cosmic rays in the metagalaxy is at least one-and-a-half orders of magnitude smaller than its galactic value. This result is another argument in favor of the conclusion drawn in [32,62] that metagalactic cosmic rays have relatively low intensity.

We note that whereas the intensity of the pionic gamma rays depends significantly on the value of a rather undetermined quantity (the concentration of the intergalactic gas), the lower limit of the intensity of the Compton gamma rays expected from the metagalaxy has been sufficiently reliably determined. In fact, the average energy density of the thermal radiation in the metagalaxy (or at any rate its lower limit) is estimated directly from the data on the luminosities of the galaxies. The possible presence of considerable radiation in the invisible sections of the spectrum merely signifies that the estimate presented above for the upper limit of the electron intensity in the metagalaxy should be reduced even more.

We note here that the contribution of the gamma radiation from all the galaxies to the intensity of the metagalactic radiation is small [32]. Thus, assuming even that within the limits of the photometric distance $R_{ph} = 5 \times 10^{27}$ cm all the galaxies with concentration $N_G \approx 5 \times 10^{-75}$ cm^{-3} have the same emission as the M31 galaxy (actually this galaxy is one of the largest), we obtain

$$I_\gamma (> 1\,\mathrm{BeV}) = N_G R_{ph} R^2 F_{\gamma, G} (> 1\,\mathrm{BeV}) \simeq 10^{-6} \frac{\text{photons}}{\text{cm}^2\text{sec}\cdot\text{sr}}. \tag{4.9}$$

Here $R \simeq 2.2 \times 10^{24}$ cm —distance to the M31 galaxy and $F_{\gamma,G}$ (> 1 BeV) $\simeq 10^{-8}$ photon/cm^{2}sec —gamma ray flux from this galaxy, which, in accordance with the estimates given in Table IV, should receive the greatest contribution from the Compton gamma rays.

Further refinement of the experimental value of the intensity I_γ (> 50 MeV), especially the separation of the anisotropic component, is of great interest. Even if the main part of the radiation is connected with the metagalaxy, the anisotropic component should undoubtedly be of galactic origin, and its separation would yield valuable information on cosmic rays, particularly their electronic component in the galaxy (we must not forget that in our calculations we extrapolated the data on cosmic rays near the earth to include the entire galaxy, something which needs further verification).

In the region of higher energies, $E_\gamma \sim 10^{11}-10^{12}$ eV, attempts were made to estimate the upper limit of the intensity of the primary electron-photon component* from the altitude variation of cosmic rays in the atmosphere [63,64]. According to [63], this intensity is less than 10% of the intensity of the primary cosmic rays of the same energy. In [64] a stronger statement is made, namely that the intensity of the primary electron-photon component does not exceed 0.1% of the intensity of the cosmic rays having the same energy (the value given in [64] is $I_{e,\gamma}$ (E > 470 BeV) < 10^{-7}cm^{-2} sec^{-1}sr^{-1}).

Although this upper limit is still much larger than the estimates given above for the expected intensity of the primary gamma rays (according to (3.13), for E = 470 BeV we have $I_{\gamma,\pi^0}(> E) \sim 4 \times 10^{-6} I(> E)$ even in the direction of the galactic center), the result of [64], if it is ever confirmed, will nonetheless be of very great significance to the clarification of the character of the spectrum of the primary electrons at high energies. We recall that in the region E < 40 BeV the electrons constitute at any rate several per cent of all the cosmic rays with specified energy.

In the energy region $E_\gamma \gtrsim 5 \times 10^{12}$ eV there are measurements [65,66] of the upper limit of the gamma ray flux from several discrete sources: A-Cygni, Crab nebula, A-Cassiopaeiae, A-Virginis, and also some of the quasars. According to [65,66] we have for these sources

$$F_\gamma (E_\gamma > 5\cdot 10^{12}\,\mathrm{eV}) < 3\cdot 10^{-10} - 5\cdot 10^{-11} \frac{\text{photons}}{\text{cm}^2\text{sec}}.$$

In the energy region under consideration, the intensity of the Compton gamma rays is already insignificant, owing to the rapid decrease in the cross section at $E_\gamma \sim E \gg 5 \times 10^{10}$ eV. The remaining processes, as can be seen from Table IV, lead even for I_γ (E > 10^9 eV) to values that are smaller than the obtained upper limit. An appreciable intensity of gamma rays with energies $E_\gamma \sim 10^{12}-10^{13}$ eV could be expected [67] in this case if all the radio-emitting electrons, for example in the radio galaxy A-Cygni or in the Crab nebula, were the result of nuclear interactions or production and decay of π^0 mesons. However, the source cosmic-ray intensity and gas mass needed for this purpose would have to greatly exceed values that are admissible from the point of view of astrophysical and radioastronomical data. In this sense, the results of [65,66], although predictable, exclude directly the possibility indicated in [67].

In the region of high energies $E_\gamma \gtrsim 10^{13}$ eV, direct measurements of the intensity of the primary gamma rays are practically impossible, because of their exceedingly low intensity. It is possible, however, to estimate this intensity, or its upper limit. from data on extensive air showers. A photon with an energy in the indicated interval will produce in the atmosphere a rather powerful electron-photon shower, which will be registered as readily as the extensive air showers due to primary nucleons and nuclei. Unlike the latter, however, photon extensive showers will contain approximately two orders of magnitude fewer muons, in accordance with the ratio of the muon photoproduction cross section and the cross section for pion production in p-p collisions (the decay of the $\pi^\pm$ mesons produced in these processes is indeed the source of the muon component of the extensive air showers).

Differentiation of extensive air showers by muon

*In the measurements in the atmosphere it was impossible to ascertain whether the primary particle was an electron or a gamma photon.

number and estimates of the upper limit of the intensity of the primary gamma quanta were made in [39-41]. The value obtained in [39,40] for the intensity $I_\gamma(E_\gamma > 10^{15}$ eV) was 10^3 times as small as the intensity of the cosmic rays of the same energy. An upper limit $I_\gamma(E_\gamma > 10^{16}\text{ eV}) < 2\times 10^{-4} I(E > 10^{16}\text{ eV})$ was obtained in [41]. It is clear from (3.13) that this upper limit is much larger than the expected intensity of gamma rays from π^0-meson decay [10] even for the direction towards the galactic center and for the metagalaxy. As to the mechanisms whereby gamma-rays connected with the electronic component of the cosmic rays of superhigh energies are generated, we must bear in mind above all that these electrons themselves would be sources of muon-poor extensive air showers. In this connection, the data of [39-41] establish also the upper limit for the intensity of the electronic component of cosmic rays on earth for the indicated energy region.

This limit is still sufficiently high and the presence of primary electrons having this intensity would not only explain the results of [39,40], but would also be the cause of a strong cyclotron x-radiation [13,14,16] of these electrons in interstellar magnetic fields (see Sec. 5). Therefore the question of the intensity of the primary electrons in the region $E \sim 10^{14}-10^{16}$ eV is particularly interesting [16].

The intensity of the secondary electrons (produced in nuclear collisions and in $\pi^\pm$-meson decay) in the energy region in question is quite small [10,38] (see also Sec. 5.1), so that in fact the entire electronic component would have to be regarded as primary and produced together with the cosmic rays in their sources. There is no need for any appreciable increase in the power of the cosmic-ray sources in this case [16]. Yet, owing to the strong cyclotron-radiation losses, the electrons with such energies cannot move far away from the sources, provided they do not move essentially at small angles to the field. Thus, the characteristic time in which the energy of an electron with initial energy $E \sim 10^{15}$ eV in a magnetic field $H \sim 3 \times 10^{-6}$ Oe is reduced by one-half amounts to

$$t \simeq \frac{4\cdot 10^{14}}{H^2 E}\text{sec} \simeq \frac{1.3\cdot 10^7}{H^2 E}\text{ years} \sim 10^3 \text{ years}. \quad (4.10)$$

Within this time, even when moving in a straight line, the electron cannot go more than 300 psec away from the source. Thus, only in the presence of cosmic ray sources that are relatively close to the solar system and "young" could we hope to observe on earth primary electrons with these energies and with an isotropic directional distribution. The presently available radioastronomical data apparently speak against the existence of such close sources (if we regard supernova flares as sources, the supernova Tycho Brahe, which is closest to the earth and which flared up in 1572, is a rather weak source and is located at ~ 360 psec).

Formula (4.10), together with the estimate based on it, pertains to the case when in the mean $H_\perp^2 = \frac{2}{3}H^2$ along the path of the electron ($H_\perp$—projection of the field H perpendicular to the electron velocity). On the other hand, if the electrons move at small angles to the field, so that $H_\perp^2 \ll H^2$, the characteristic time for the energy loss increases noticeably. Therefore the high-energy electrons, with velocity directed along the arm of the spiral in which the sun is located (it is assumed here that a quasi-regular field directed along the arm exists), could arrive to us from large distances. Here, obviously, the intensity of the electrons will be essentially anisotropic. We note, in addition, that the very possibility of generation of electrons with energies $E \sim 10^{14}-10^{16}$ eV in cosmic-ray sources has, generally speaking, a low probability, primarily because of the strong cyclotron-radiation losses (the magnetic-field intensity in the sources is appreciably higher than in the interstellar space). On the other hand, if we admit of such a possibility, then the gamma bremsstrahlung and cyclotron x-radiation produced by these electrons (see Sec. 5) should be nonstationary and localized in individual regions near supernovas, inasmuch as the frequency of supernova flares in the galaxy is merely one every 100–300 years.

5. X RADIATION CONNECTED WITH COSMIC RAYS

5.1. Cyclotron X-Radiation

As is well known, non-thermal cosmic radio emission, and in the case of some objects also optical radiation, have a cyclotron-radiation nature. It is not unlikely that conditions are realized in the universe under which the cyclotron-radiation mechanism can be responsible also for emission at x-ray wavelengths. Let us consider these conditions.

The cyclotron-radiation spectrum of an ultrarelativistic electron has a rather sharply pronounced maximum. The total electron energy E is expressed in terms of the frequency ν (in cps) at which the maximum intensity occurs, by the relation [see (2.6)]

$$E \simeq 7.5\cdot 10^{-10}\left(\frac{\nu}{H_\perp}\right)^{1/2}\text{erg} \simeq 4.7\cdot 10^2\left(\frac{\nu}{H_\perp}\right)^{1/2}\text{eV}, \quad (5.1)$$

where $H_\perp$ (in Oe)—magnetic field component perpendicular to the electron velocity. In first approximation we can assume that the entire power radiated by the electron

$$P \equiv \int_0^\infty P(\nu)\,d\nu = -\frac{dE}{dt} = 1.6\cdot 10^{-15} H_\perp^2 \left(\frac{E}{mc^2}\right)^2 \frac{\text{erg}}{\text{sec}}$$

$$\simeq 10^{-3} H_\perp^2 \left(\frac{E}{mc^2}\right)^2 \frac{\text{eV}}{\text{sec}} \quad (5.2)$$

occurs at a frequency ν corresponding to the maximum in the spectrum. Then (5.1) provides a unique connection between the frequency and the energy of the radiating electrons (for more details see [32]).

For a power-law electron spectrum

$$N_e(E)\,dE = \frac{4\pi}{c} I_e(E)\,dE = \widetilde{K}_e E^{-\gamma}\,dE \qquad (5.3)$$

the cyclotron-radiation intensity is determined in the isotropic case by the expression [32]

$$J(\nu) = 1.35 \cdot 10^{-22} a(\gamma)\, L\widetilde{K}_e H^{\frac{\gamma+1}{2}} \left(\frac{6.26 \cdot 10^{18}}{\nu}\right)^{\frac{\gamma-1}{2}} \frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{sr}\cdot\text{cps}}, \qquad (5.4)$$

where $a(\gamma)$ —numerical coefficient with values $a(2.5) = 0.085$, $a(3) = 0.074$, and $a(4) = 0.072$; L —length of the radiating region along the line of sight, and $\widetilde{K}_e$ — coefficient contained in (5.3) with dimension $(\text{erg})^{\gamma-1}\,\text{cm}^{-3}$. It is assumed in (5.4) that the electrons are uniformly and isotropically distributed along the line of sight L, and that the magnetic field H is constant in magnitude and randomly distributed in direction.

Formula (5.4) can be readily obtained, apart from a numerical coefficient of the order of unity (see the analogous calculation in Sec. 3.3), from expressions (5.1)—(5.3) by putting $p(\nu) = P\delta(\nu - \nu(E))$, where $\nu(E)$ is determined from (5.1).

We shall be interested in x-rays with frequencies on the order of $\nu = 10^{18}$ cps ($\lambda = 3\,\text{Å}$, $E = h\nu = 4$ keV).

We consider first conditions under which the cyclotron x-radiation of the electrons occurs in interstellar space.

By way of the mean value of $H_\perp$ in interstellar space (we are referring essentially to the region of the galactic disc; see below) we can assume $H_\perp \sim 5 \times 10^{-6}$ Oe. Then by virtue of (5.1) the frequencies $\nu \sim 10^{18}$ cps will be radiated only by electrons with energies $\sim 2 \times 10^{14}$ eV. In the region of such energies we can estimate with sufficient reliability only the number of secondary electrons—the products of the $\pi \to \mu \to e$ decay. Let us estimate this number and the x-ray intensity produced by these electrons.

To this end we use expression (3.3) for the intensity of the pions produced by the cosmic rays on a unit path, and we assume that $^2\!/_3$ of these pions are charged. Taking into account the kinematics of the $\pi^\pm \to \mu^\pm + \nu$ and $\mu^\pm \to e^\pm + \nu + \bar{\nu}$ decays, the intensities of the electrons and pions produced on a unit path are related by the equation [10]

$$q_e(E)\,dE = \varkappa(\gamma_\pi)\, q_{\pi^\pm}(E)\,dE, \qquad (5.5)$$

where the coefficient $\kappa(\gamma_\pi)$, which depends on the exponent γ_π in the power-law pion spectrum, is equal to

$$\varkappa(\gamma) = \left(\frac{m_\mu}{m_\pi}\right)^{\gamma-1} \frac{2(\gamma+5)}{\gamma(\gamma+2)(\gamma+3)}, \quad \varkappa(2.8) \simeq 0.12 \qquad (5.6)$$

(here m_μ and m_π —rest masses of the μ and π mesons).

For the spectrum (3.3), assuming $\sigma = 3 \times 10^{-26}$, we get

$$q_e(E) \simeq 3 \cdot 10^{-28} n(\mathbf{r})\, E^{-2.8} \frac{\text{electrons}}{\text{cm}^3\text{sec}\cdot\text{sr}\cdot\text{BeV}} \ (E \text{ in BeV}) \qquad (5.7)$$

or

$$q_e(E) \simeq 2.8 \cdot 10^{-33} n(\mathbf{r})\, E^{-2.8} \frac{\text{electrons}}{\text{cm}^3\text{sec}\cdot\text{sr}\cdot\text{erg}} \ (E \text{ in erg}),$$

where $n(\mathbf{r})$ —concentration of interstellar gas as a function of the coordinates.

The spectrum (5.7) is a generation spectrum, and when multiplied by 4π is equal to the number of electrons and positrons of energy E, produced per unit time in a unit volume. In order to determine the concentration of the electrons $N_e(E)$ [or their intensity $I_e(E)$, see (5.3)] under conditions of stationary generation, it is necessary to take into account the electron energy losses. For the energies $E \sim 10^{14}$ eV in question, the radiation and Compton energy losses in interstellar space are much lower than the cyclotron-radiation losses (5.2). As regards the diffusion escape of particles from the galaxy, for electrons with $E \sim 10^{14}$ eV it plays practically no role, inasmuch as during the characteristic time of the cyclotron-radiation losses (4.10) the electrons cannot move any appreciable distance away from their point of generation (in this connection, the secondary electrons with these energies, and the cyclotron x-radiation produced by them, are concentrated principally in the galactic disc, where the greater part of the interstellar gas is located).

Under stationary conditions, taking into account the cyclotron-radiation losses, the spectrum of the electrons in the interstellar space is determined by the equation

$$-\frac{\partial}{\partial E}\{\beta E^2 N_e(E)\} = 4\pi q_e(E), \qquad (5.8)$$

where $\beta = 2.4 \times 10^{-3} H_\perp^2\,(\text{erg.sec})^{-1}$ —coefficient in the expression $-dE/dt = \beta E^2$ for the cyclotron-radiation losses [see (5.2)]. According to (5.7) and (5.8) we have

$$N_e(E) = \frac{4\pi}{\beta E^2} \int_E^\infty q_e(E')\,dE', \qquad (5.9)$$

$$N_e(E) \simeq 3 \cdot 10^{-19} n(\mathbf{r})\, E_{\text{erg}}^{-3.8} \frac{1}{\text{cm}^3.\text{erg.}}$$

$$\simeq 2 \cdot 10^{-11} n(\mathbf{r})\, E_{\text{BeV}}^{-3.8} \frac{1}{\text{cm}^3\text{BeV}}, \qquad (5.10)$$

where we put $H_\perp = 5 \times 10^{-6}$ Oe.

Substituting the obtained value $\widetilde{K}_e = 3 \times 10^{-19} n(\mathbf{r})$ [see (5.3) and (5.10)] into the expression for the intensity (5.4) and putting

$$H = \left(\frac{3}{2} H_\perp^2\right)^{1/2} \simeq 6 \cdot 10^{-6},$$

we obtain

$$\left.\begin{aligned} J(\nu) &\simeq 2 \cdot 10^{-28} N(L)\, \nu^{-1.4} \frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{sr}\cdot\text{cps}}, \\ I(\nu) &= \frac{I(\nu)}{h\nu} = 3 \cdot 10^{-2} N(L)\, \nu^{-2.4} \frac{\text{quanta}}{\text{cm}^2\text{sec}\cdot\text{sr}\cdot\text{cps}}, \end{aligned}\right\} \qquad (5.11)$$

$$\left.\begin{aligned} J(>\nu) &\simeq 5 \cdot 10^{-28} N(L)\, \nu^{-0.4} \frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{sr}}, \\ I(>\nu) &= 2 \cdot 10^{-2} N(L)\, \nu^{-1.4} \frac{\text{quanta}}{\text{cm}^2\text{sec}\cdot\text{sr}}. \end{aligned}\right\} \qquad (5.12)$$

In particular, for x-ray quanta with frequencies $\nu > 3 \times 10^{17}$ cps ($\lambda < 10$ Å, $E > 1.25$ keV) we have

$$\left.\begin{aligned} J(\nu > 3\cdot 10^{17}) &= 5\cdot 10^{-35} N(L) \frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{sr}}, \\ I(\nu > 3\cdot 10^{17}) &= 7\cdot 10^{-27} N(L) \frac{\text{quanta}}{\text{cm}^2\text{sec}\cdot\text{sr}}, \end{aligned}\right\} \quad (5.13)$$

that is, the intensity of such quanta is quite low even in the direction of the galactic center.

$$\left.\begin{aligned} I(\nu > 3\cdot 10^{17}) &\simeq 2\cdot 10^{-4} \frac{\text{quanta}}{\text{cm}^2\text{sec}\cdot\text{sr}}, \\ J(\nu > 3\cdot 10^{17}) &\simeq 1.5\cdot 10^{-12} \frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{sr}}. \end{aligned}\right\} \quad (5.14)$$

As can be seen from (5.10) and (2.1), the ratio of the intensities of the secondary electrons and of the protons with energies above a specified value is

$$\frac{I_e(>E)}{I_p(>E)} \simeq 2\cdot 10^{-2} n(\mathbf{r}) E^{-1.2}, \quad (5.15)$$

where the energy E is in BeV. For $E = 2 \times 10^{14}$ eV $= 2 \times 10^5$ BeV, this ratio is equal to $\sim 10^{-8} n(r)$, that is, the intensity of the secondary electrons in the energy region in question is $\sim 10^{-8}$ of the cosmic-ray intensity even in the central part of the galactic disc, where the concentration reaches $n \sim 1$ cm^{-3}.

The foregoing still does not mean that the cyclotron x-radiation from interstellar space does not play any role at all. The point is that in principle the electrons generating this radiation can be not secondary but primary (that is, produced in the cosmic-ray sources). This possibility was already mentioned in Sec. 4.3. If we assume, by way of an example that does not contradict the data on muon-poor extensive air showers, that the intensity of the primary electrons is $\sim 10^{-4}$ of the intensity of all the cosmic rays having the same energy, then the intensity of the cyclotron radiation of these electrons will be approximately 10^4 times larger than the intensity (5.13), and will reach in the direction of the galactic center a value of several quanta/cm^2 sec-sr. But, as already noted in Sec. 4.3, the presence in interstellar space of electrons with energy $\sim 10^{14}$ eV and with the indicated intensity has very low probability.

In this connection, great interest attaches to a consideration of such objects as supernovas, radio galaxies, and exploding galactic cores as possible sources of cyclotron x-radiation. If we assume that there exist in such objects regions in which the magnetic field intensity reaches $H \simeq 10^2$ Oe and higher (this is quite probable under gravitational compression and collapse of an initially massive star [68]) then, as can be seen from (5.1) the x-radiation with frequency $\nu \simeq 10^{18}$ will be produced even by electrons with energy $E \sim 5 \times 10^{10}$ eV. Electrons with such energies are contained in the envelopes of supernovas, as is well known with the Crab nebula as an example. Let us consider this example in greater detail [24].

The cyclotron-radiation flux from a source located at a distance R is

$$\Phi(\nu) = 1.35\cdot 10^{-22} a(\gamma) \frac{\widetilde{K}_e V H^{\frac{\gamma+1}{2}}}{R^2} \left(\frac{6.26\cdot 10^{18}}{\nu}\right)^{\frac{\gamma-1}{2}} \frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{cps}}, \quad (5.16)$$

where V—volume of the source and $\widetilde{K}_e$—coefficient in the electron spectrum (5.3) per unit volume. We assume that the electrons fill uniformly the volume V of the source, but that in a small part of the volume $V_1 \ll V$ the magnetic field intensity is $H_1 \gg H$, where H—average field intensity in the volume V. Then the ratio of the radiation fluxes from the volume V_1 at frequency ν_1 and from the total volume V at frequency ν is equal to

$$\frac{\Phi(\nu_1)}{\Phi(\nu)} = \frac{V_1}{V}\left(\frac{H_1}{H}\right)^{\frac{\gamma+1}{2}}\left(\frac{\nu}{\nu_1}\right)^{\frac{\gamma-1}{2}}. \quad (5.17)$$

For the Crab nebula (see, for example, [32]) the flux of radio emission at frequency $\nu = 10^8$ cps is equal to 1.7×10^{-20} erg/cm^2 sec-cps, the volume is $V = 6.6 \times 10^{55}$ cm^3, the magnetic field intensity is $H = 1.4 \times 10^{-3}$ Oe, and the exponent is $\gamma = 2\alpha + 1 = 1.7$ (the spectral index is $\gamma = 0.35$). Putting $\nu_1 = 10^{18}$ cps and $H_1 = 10^2$ Oe, we get

$$\Phi(10^{18}\text{ cps}) = 1.9\cdot 10^{-17}\cdot\frac{V_1}{V}\frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{cps}}. \quad (5.18)$$

The resultant x-ray flux is equal in order of magnitude to the flux Φ (10^{18} cps) $\simeq 2 \times 10^{-9}$ erg/cm^2 sec-Å $\simeq 6 \times 10^{-27}$ erg/cm^2 sec-cps, observed in [69] if $V_1 \simeq 3 \times 10^{-10} V \simeq 2 \times 10^{46}$ cm^3. For example, if the volume V_1 is a spherical region with a strong magnetic field near a collapsing star, then the effective radius of this region should be equal to

$$R_1 \simeq \left(\frac{V_1}{V}\right)^{1/3} R \simeq 10^{15}\,\text{cm},$$

where $R \simeq 2.5 \times 10^{18}$ cm—radius of the radio-emitting nebula.

According to (4.10), the characteristic time t relative to cyclotron-radiation losses for electrons with energies $E \sim 5 \times 10^{10}$ eV, in a field $H \sim 10^2$ Oe, is approximately 1 second. This means that if the electrons with the energies in question enter into a volume V_1 from a "reservoir" with volume V, the time during which all the electrons will be drawn out is approximately $Vt/V_1 \sim 10^3$ years (of course, if we neglect the possibility of electron influx during that time). These estimates are of course only tentative. Thus, for example, by choosing a field H equal to 10 Oe, which is perfectly admissible (this is precisely the value used for the field in [24]), we obtain an electron lifetime t $\sim 10^2$ sec. The field energy $H_1^2 V_1/8\pi$ is equal to 10^{49} erg for the case considered above, whereas for the entire nebula $H^2V/8\pi \simeq 5 \times 10^{48}$ erg. On the other hand, if we put $H_1 = 10$ Oe, then $V_1 \simeq 5 \times 10^{47}$ cm^3 and $H_1^2 V_1/8\pi \simeq 2 \times 10^{48}$ erg. Thus, this model apparently raises no difficulties when it comes to energy. However, the assumption that there exists a rather strong field $H_1 \sim 10$–100 Oe in a region with dimensions

$10^{15}-10^{16}$ cm for stars with not too large a mass does not follow directly from known estimates (see [24], [68], and the bibliography cited in [24]). On the other hand, the field in the central part of the envelope can be greatly decreased by assuming that there exist in this region electrons with sufficiently high energy. Summarizing, we can only state that the cyclotron-radiation model of a discrete x-ray source and the foregoing estimates do not contradict the known data on the Crab nebula. We must therefore admit of the possibility that discrete sources of radio emission can simultaneously be also sources of strong x-radiation even without making use of the hypothesis that hot neutron stars exist in these sources (see Sec. 5.3 and the note added in proof at the end of the article).

5.2. X-Radiation Due to Other Processes

As a result of the processes considered in Chapter 3 cosmic rays will, of course, make also some contribution to the x-radiation. It will now be shown that this contribution is small.

In the case of π^0-meson decay, this can be easily verified by recognizing that in the π^0-meson rest system the energy of the produced gamma photons is $E_{\gamma,0} \simeq 70$ MeV. Therefore in the laboratory system, photons with x-ray energies will be produced only by decay of sufficiently fast π^0 mesons, and will at the same time be emitted in a direction opposite to the direction of motion of these mesons. The laboratory energy of the photon is

$$E_\gamma \geqslant E_{\gamma,0}\left(z-\sqrt{z^2-1}\right) \simeq \frac{E^2_{\gamma,0}}{E_\pi}, \qquad (5.19)$$

where $z = E_\pi/m_\pi c^2 = E_\pi/2E_{\gamma,0}$; on going over to the last expression we assumed $z \gg 1$, corresponding to the case $E_\gamma \ll E_{\gamma,0}$ of interest to us; the equality sign in the left side of (5.19) holds when the photon is emitted strictly backwards relative to the π^0-meson velocity. According to (5.19), photons with energy $E_\gamma \lesssim 13$ keV ($\lambda \gtrsim 1$ Å) are produced only from π^0 mesons with energies $E_\pi \gtrsim 400$ BeV. The number of such π^0 mesons is small compared with their total number [see (3.7) and (3.8)]. Therefore the intensity of the x-ray quanta produced in this process is considerably lower than the total intensity of the gamma quanta (4.4), and is small even compared with the intensity of the cyclotron x-radiation of the secondary electrons [see (5.13)].

The lower limit of the intensity of the x-radiation due to the bremsstrahlung of relativistic electrons can be obtained by taking into account only the electronic component of the cosmic rays in the energy region $E > 0.5$ BeV. The total intensity of the electrons with such energies is, according to (2.7),

$$I_e(>0.5\,\mathrm{BeV}) \simeq 10^{-2}\,\frac{\text{electrons}}{\text{cm}^2\text{sec}\cdot\text{sr}}. \qquad (5.20)$$

We note here that the total intensity of secondary electrons (with energies $E > mc^2$), produced in the galaxy at a rate[38] $\tilde{q}_e V \sim 9 \times 10^{14}$ electrons/sec, is equal to

$$I_{e,\pi^\pm}(E > mc^2) = \frac{c}{4\pi} N_{e,\pi^\pm}(>mc^2) = \frac{c}{4\pi}\tilde{q}_e T_{es} \simeq 4\cdot 10^{-3}\,\frac{\text{electrons}}{\text{cm}^2\text{sec}\,.\,\text{sr}}$$

(we assume here that the electron moves within the confines of the galaxy, the volume of which is $V \simeq 5 \times 10^{68}$ cm^3, during a time $T_{es} \simeq 3 \times 10^8$ years). Thus, an account of the secondary electrons with arbitrary energies does not change appreciably the estimates that follow. As to the primary electrons with energies $E < 0.5$ BeV, there are no data whatever at present on such (subcosmic) particles. Therefore this estimate provides only the lower limit of the intensity of the x-ray bremsstrahlung.

For the case of interest to us $E_\gamma \ll mc^2 \ll E$, total screening takes place and we can use expressions (3.17) and (3.18). Together with (5.20), this yields

$$\left.\begin{aligned} I_{\gamma,\,\mathrm{br}}\,(E_\gamma) &= 1.5\cdot 10^{-4} M(L)\,E_\gamma^{-1},\\ J_{\gamma,\,\mathrm{br}}\,(E_\gamma) &= E_\gamma I_{\gamma,\,\mathrm{br}}\,(E_\gamma) = 1.5\cdot 10^{-4} M(L),\\ J_{\gamma,\,\mathrm{br}}\,(<E_\gamma) &= \int_0^{E_\gamma} J_{\gamma,\,\mathrm{br}}\,(E_\gamma)\,dE_\gamma = 1{,}5\cdot 10^{-4} M(L)\,E_\gamma. \end{aligned}\right\} \qquad (5.21)$$

In particular, for $E_\gamma < 12.5$ keV $\simeq 2 \times 10^{-8}$ erg ($\lambda > 1$ Å, $\nu < 3 \times 10^{18}$ cps), we obtain

$$J_{\gamma,\,\mathrm{br}}\,(\nu < 3\cdot 10^{18}) = 3\cdot 10^{-12} M(L)\,\frac{\text{erg}}{\text{cm}^2\text{sec}\cdot\text{sr}}. \qquad (5.22)$$

We see from a comparison of (5.22) and (5.13) that in the interval $\lambda = 1-10$ Å the intensity of the bremsstrahlung is approximately one order of magnitude lower than the intensity of the x-ray cyclotron radiation of the secondary electrons. However, owing to the different character of the radiation spectra (in the case of bremsstrahlung the intensity $J(E_\gamma)$ does not depend on the quantum energy E_γ, while in the case of cyclotron radiation it decreases with increasing E_γ), the bremsstrahlung becomes stronger than the cyclotron radiation with increasing photon energy.

Let us estimate finally the intensity of the x-radiation produced by Compton scattering of thermal photons in interstellar space by relativistic electrons. The x-ray quanta with energies $E_\gamma > 1.25$ keV ($\lambda < 10$ Å) are produced according to (3.23), when $\bar{\epsilon} \sim 1$ eV, by electrons with energies $E \gtrsim 15$ MeV. According to (3.25) we have

$$I_\gamma(>E_\gamma) = \int_{E_\gamma}^{\infty} I_\gamma(E_\gamma)\,dE_\gamma = N_{\mathrm{ph}}(L)\,\sigma_T I_e\left(E > mc^2\sqrt{\frac{3}{4}\frac{E_\gamma}{\bar{\varepsilon}}}\right). \qquad (5.23)$$

For secondary electrons, the generation spectrum of which has a maximum at $E \sim 30$ MeV and decreases with decreasing energy[38], we can use for $I_e(>E)$ with $E \lesssim 30$ MeV the value $I_{e,\pi^\pm}(>mc^2) = 4 \times 10^{-3}$ electron/cm^2 sec-sr obtained above. As a result we have for Compton x-rays from secondary electrons

$$\left. \begin{aligned} I_\gamma(\nu > 3\cdot 10^{17}\,\mathrm{cps}) &= 2.7\cdot 10^{-27} N_{\mathrm{ph}}(L)\,\frac{\mathrm{photons}}{\mathrm{cm^2 sec\cdot sr}} \\ &\simeq 4\cdot 10^{-5}\,\frac{\mathrm{photons}}{\mathrm{cm^2 sec\cdot sr}}, \end{aligned} \right\} \quad (5.24)$$

where we put $N_{ph}(L) = 1.4 \times 10^{22}$, corresponding to the directions of the center and of the pole of the galaxy.

Primary high-energy electrons [see (5.20)] make also formally a contribution to I_γ ($\nu > 3 \times 10^{17}$ cps), but in fact lead essentially to the appearance of gamma rays with energy $E_\gamma \sim \bar{\epsilon}\,(E/mc^2)^2 \gtrsim 10^6$ eV. For the x-ray region it is therefore necessary to use just the estimate (5.24) if we disregard, of course, subcosmic primary electrons. Unlike cyclotron x-radiation from secondary electrons [see (5.14)], the intensity of the Compton photons (5.24) is approximately isotropic and when averaged over the directions is approximately 7 times larger, although in the direction of the galactic center the cyclotron x-radiation plays the main role as before.

5.3. Comparison of Calculations with Observations

In 1962—1963, as a result of measurements made with rockets outside the atmosphere [4,69,70], cosmic x-radiation was observed in the wavelength band $\lambda = 2—8$ Å (the effective wavelength corresponding to the maximum sensitivity of the detector employed was $\lambda_{ef} \simeq 3$ Å). In [70] the band was broadened to $\lambda \approx 0.12$ Å. The observed x-radiation can be divided into two principal components: isotropic radiation (background) and radiation arriving from several fixed directions on the celestial sphere.

The isotropic x-radiation is apparently of cosmic origin and is characterized by an intensity [69,70]

$$I(2\,\text{Å} < \lambda < 8\,\text{Å}) \simeq 6\,\frac{\mathrm{quanta}}{\mathrm{cm^2 sec\cdot sr}}. \quad (5.25)$$

The radiation from the fixed regions on the celestial sphere is naturally connected with discrete sources, the possible nature of which will be discussed briefly at the end of this section. The most powerful of these sources is located in the Scorpion constellation. The experimental accuracy with which the angular position and the dimensions of the source have been determined is low (on the order of 5°), but in this region of the sky there are neither bright nebulas nor powerful radio sources. The x-ray flux from the source in the Scorpion constellation is equal to

$$F(2\,\text{Å} < \lambda < 8\,\text{Å}) \simeq 20\,\frac{\mathrm{photons}}{\mathrm{cm^2 sec}},$$

$$\Phi(2\,\text{Å} < \lambda < 8\,\text{Å}) \simeq 1.3\cdot 10^{-7}\,\frac{\mathrm{erg}}{\mathrm{cm^2 sec}},$$

where the effective wavelength is taken to be $\lambda_{ef} = 3$ Å ($\nu = 10^{18}$ cps, $E = 6.62 \times 10^{-9}$ erg $= 4.14$ keV). In the region of shorter wavelengths we have, according to [70]

$$F(\lambda < 1.8\,\text{Å}) \leqslant 0.30 \pm 0.08\,\frac{\mathrm{photons}}{\mathrm{cm^2 sec}}.$$

In addition to this source, two less powerful sources were observed: in the direction of the filamentary nebula in the Cygnus constellation and in the direction of the Crab nebula. According to [69], the flux from the source in the Crab nebula is $\Phi(\lambda) = 2 \times 10^{-9}$ erg/cm² sec. Å for the wavelength interval $1.5\,\text{Å} < \lambda < 8\,\text{Å}$.

As follows from the estimates made in Secs. 5.1 and 5.2 [see (5.14) and (5.24)], the x-radiation intensity connected with the cosmic rays or with their electronic component is four or five orders of magnitude lower than the intensity (5.25) observed in [4,69,70]. Even if we assume that in the energy region $E \gtrsim 10^{14}$ eV an appreciable role is played by primary electrons, the intensity of which in the galactic disc is four orders of magnitude larger than the intensity of the secondary electrons (5.10) (see Sec. 5.1), the cyclotron radiation produced by them will have an intensity corresponding to (5.25) only in the direction of the galactic center. On the other hand, in the direction of the anticenter, and all the more in the direction of the pole of the galaxy, the intensity should be appreciably lower, if we take into account (as is apparently inevitable) the sources of the primary electrons connected with the stellar population of the galaxy.

It was assumed in [14] that the primary electrons fill a spherical or quasispherical volume (the latter with a semiaxis ratio 0.6), that is, they fill both the disc and the galactic halo. If we take into account the rate of energy loss for electrons with $E \gtrsim 10^{14}$ eV [see (4.10)], this is tantamount to assuming that sources of such electrons are present in the halo. However, whereas we can assume, by stretching the point somewhat, that the electrons can be accelerated to an energy $E \sim 10^{14}$ eV near stars (primarily supernovas), there are no grounds whatever for such an assumption under the conditions of the halo.

Thus, the observed intensity and isotropy of the background x-radiation (5.25) cannot be explained by attributing this radiation to galactic cosmic rays.

The high degree of isotropy of the observed x-ray background (if it actually exists) apparently excludes completely its galactic origin, even if we connect this radiation with subcosmic particles [25,26,52]. Therefore isotropic x-radiation with intensity (5.25), assuming its extraterrestrial origin is proved, is more likely to have a metagalactic nature and is either connected with subcosmic particles [52,26,74], or is the summary radiation from a large number of discrete sources of the type observed in [4,69,70], uniformly distributed in the metagalaxy [26]. If the isotropic x-ray background is of metagalactic origin, a study of its spectrum with allowance for the influence of absorption can yield valuable information on the concentration of neutral hydrogen in the intergalactic space [26,71]. Various assumptions were advanced concerning the discrete x-ray sources observed in [4,69,70]. Thus, it is assumed in [58] that supernova stars not observed in the radio band because of the steep energy spectrum of the electrons can produce a sufficiently powerful bremsstrahlung or Compton radiation. In [72] are considered double stars of the early type, for which the collision of expanding atmospheres can lead to a strong x-ray bremsstrahlung. However, the greatest attention has been paid in the literature to hot neutron stars as being the probable sources of powerful thermal x-radiation[21,22,73].

The black-body radiation from a neutron star will have a maximum intensity at a wavelength $\lambda_m \simeq 3\,\text{Å} = 3 \times 10^{-8}$ cm, if the temperature of its surface (photosphere) is

$$T = \frac{0.29}{\lambda_m} \simeq 10^7\,{}^\circ\text{K}. \qquad (5.26)$$

According to the Stefan-Boltzmann law, the power radiated from a star of radius r and temperature T is $4\pi r^2 \sigma T^4$, where $\sigma = 5.67 \times 10^{-5}$ erg/cm²sec-deg⁴. The radiation flux at a distance R from the star will therefore be equal to

$$\Phi = \left(\frac{r}{R}\right)^2 \sigma T^4. \qquad (5.27)$$

Thus, the x-ray flux $\Phi \simeq 1.3 \times 10^{-7}$ erg/cm² sec observed in [69,70] can be connected with a neutron star having a surface temperature $T = 10^7$ deg K and a radius r = 10 km, provided the star is located at a distance $R = 2.1 \times 10^{21}$ cm $\simeq$ 700 psec.

According to [21,73] the cooling time of a neutron star produced as a result of a gravitational collapse, for example in a supernova or nova flare, is approximately 10^3 years. If the three observed sources of [69,70] are neutron stars with $T \lesssim 2 \times 10^7$ deg K, then these stars should be located in a region with radius ~1 kpsec and a volume 4 kpsec³ near the sun. Then the total number of hot neutron stars in the galactic disc (disc volume ~300 kpsec³) should be of the order of 100, and the frequency of their appearance (for a lifetime of 10^3 years) is approximately $\frac{1}{10}$ per year. The frequency of supernova flares in the galaxy is on the order of 10^{-2} annually. Therefore, taking into account the tentative character of this estimate, we can still not state that the number of neutron stars contradicts the data on the supernovas. Moreover, it must be borne in mind that neutron stars are perhaps formed as a result of some nova flares. The number of the appearances of the latter in the galaxy is of the order of 100 annually.

At the end of Sec. 5.1 we discussed still another hypothesis concerning the nature of the discrete x-ray sources, namely, we considered the cyclotron-radiation model[24] of such a source. Although in this model the angular dimensions of the source, do exceed the dimensions of the neutron star by many orders of magnitude, they are still very small in absolute magnitude (for the source in the Crab nebula, the angular dimension of the cyclotron-radiation x-ray source would amount to approximately 2″). From the point of view of the possibility of the experimental verification, an important difference between sources of both types is that their spectra are different, and also that the x-rays from the cyclotron-radiation source may be polarized (see note added in proof at the end of the article).

CONCLUSION

Gamma and x-ray astronomy, as follows from the foregoing, have appreciable potential uses. Let us list here the most important trends in the research.

1. Measurements of the intensity $I_\gamma(E_\gamma)$ in the energy region $E_\gamma \gtrsim 1$ MeV yield information on the concentration and spectrum of relativistic electrons in metagalactic space, something so far unattainable by other methods. When $E_\gamma > 50$ MeV, the intensity $I_\gamma(E_\gamma)$ already depends also on the intensity of the proton-nuclear component of the cosmic rays, which likewise uncovers prospects with respect to study of metagalactic space.

By separating the galactic component of the gamma-ray intensity, which is feasible in principle by virtue of the anisotropy of the intensity, we can appreciably refine and check the available data and concepts concerning cosmic rays in the galaxy, and particularly their electronic component in the galactic halo.

2. By determining the x-ray intensity we can obtain information, hitherto completely lacking, on subcosmic particles ($E < 3 \times 10^8$ eV) in the galaxy and metagalaxy.

3. Observations of the annihilation line $E_\gamma = 0.51$ MeV would yield valuable information on the intensity of cosmic rays in the galaxy 10^9 years ago, and also on the rate of escape of cosmic rays from the galaxy.

4. Discrete sources of x-rays attract special interest. In particular, detection of any remote neutron star can be effected at present, if at all, apparently only in the x-ray region.

5. If the optical radiation of quasars is of cyclotron-radiation origin, these objects may turn out to be rather powerful sources of gamma rays.

There are also other interesting problems in the field of gamma and x-ray astronomy (radiation from the sun, total radiation from the stars, gamma radiation of high energy in regions with $E_\gamma > 10^{11}$ eV and $E_\gamma > 10^{14}$ eV, and a few others).

All this allows us to think that a study of cosmic gamma and x-radiation constitutes an important trend in modern astronomy.

Note added in proof. According to information recently obtained, measurements were made in the USA of intensity of x-radiation of the Crab nebula during its occultation by the moon. The fact that such measurements were being planned was mentioned in [76]. These observations, according to preliminary data, offer evidence that the discrete x-ray source in the Crab nebula is not pointlike — its diameter reaches 1/5 of the diameter of the optical source. The hypothesis that the x-ray source in Crab is a neutron star is eliminated by the same token. As we have seen in Secs. 5.1 and 5.3 (see also [24, 58, 72, 76, 77]), even before these measurements were made the assumption of the neutron nature of the x-ray source in

Crab was not regarded at all as being the only one possible; it was subject, in addition, to certain objections [78, 79] with respect to the calculation of the temperature of the neutron star. Thus, it was shown in [79] that the neutron star is probably in a superfluid state. In this case the published temperature calculations are incorrect.

In Secs. 5.1 and 5.3 we discussed a model in which the x-ray source in Crab has a cyclotron-radiation nature. The x rays were then assumed to be due to the same relativistic electrons which produced the optical cyclotron radiation. By the same token, the cyclotron-radiation x rays from Crab could be explained even without assuming that this source contained electrons with energies $E \gg 10^{11}$ eV. The true situation, however, is apparently simply that there are in Crab electrons with sufficiently high energies to produce cyclotron emission of x rays in fields of 10^{-2}–10^{-3} Oe.

Inasmuch as the volume of the x-ray source is still approximately 1/100 of the volume of the entire nebula, it is natural to assume that, as in the model of [24], the field in the central part of the envelope was stronger than the average field of 10^{-3}–10^{-4} Oe, which corresponds to the entire envelope. As shown by L. M. Ozernoĭ, if we use formula (5.17) and set the spectral index of the optical and x-ray cyclotron radiation of Crab equal to $\alpha = 1.5$ (consequently $\gamma = 2\alpha + 1 = 4$), then the observed intensity of the x rays is found to correspond to a field $H_{\perp} = 3 \times 10^{-2}$ Oe. This field should exist in the entire volume of the x-ray source. The cyclotron-radiation model of the x-ray source in Crab was considered also in [77].

Of course, the cyclotron-radiation nature of the x-ray source in Crab has not yet been proved, but at present it is the most likely. At the same time, it is necessary to assume in this case that relativistic electrons with energy region 10^{13} eV are present in Crab. The lifetime of such electrons does not exceed several years, and thus the particles should be continuously accelerated in the source. The role of such an accelerator is possibly played by a collapsing magnetic star [24, 68].

1 G. M. Nikol'skiĭ, Geomagnetizm i aĕronomiya **2**, 3 (1962); DAN SSSR 151, 536 (1963), Soviet Phys. Doklady **8**, 646 (1964).

2 M. R. Kundu, Space Sci. Rev. **2**, 438 (1963).

3 L. E. Peterson and J. R. Winckler, J. Geophys. Res. **64**, 697 (1959).

4 Giacconi, Gursky, Paolini, and Rossi, Phys. Rev. Letts **9**, 439 (1962); **11**, 530 (1963).

5 W. L. Kraushaar and G. W. Clark, Phys. Rev. Letts. 8, 106 (1962); Proc. Intern. Conf. on Cosmic Rays, Jaipur, India, 1963.

6 Arnold, Metzger, Anderson and Van Dilla, J. Geophys. Res. **67**, 4878 (1962).

7 S. Hayakawa, Progr. Theor. Phys. **8**, 517 (1952).

8 P. Morrison, Nuovo cimento **7**, 858 (1958).

9 K. Greisen, Ann. Rev. Nucl. Sci. **10**, 63 (1960).

10 V. L. Ginzburg and S. I. Syrovat-skiĭ, JETP **45**, 353 (1963), Soviet Phys. JETP **18**, 245 (1964).

11 J. E. Felten and P. Morrison, Phys. Rev. Letts. **10**, 453 (1963).

12 S. Hayakawa, Phys. Letts. **1**, 234 (1962); S. Hayakawa and Y. Yamamoto, Progr. Theor. Phys. **30**, 71 (1963).

13 G. W. Clark, Nuovo cimento **30**, 727 (1963).

14 M. W. Friedlander, Nuovo cimento (in press); Preprint 1963.

15 E. Schatzman, Space Sci. Rev. **1**, 774 (1963).

16 V. L. Ginzburg and S. I. Syrovat-skiĭ, JETP **46**, 1865 (1964), Soviet Phys. JETP **19**, 1255 (1964).

17 J. V. Jelley and N. A. Porter, Quart. J. Roy. Astron. Soc. **4**(3), 275 (1963).

18 N. A. Vlasov, Optical Method of Prospecting for Antimatter in the Universe, Preprint, Institute of Atomic Energy, 1963.

19 I. M. Gordon, Astron. zh. **37**, 934 (1960), Soviet Astronomy **4**, 874 (1960).

19a V. V. Zheleznyakov, On the Mechanism of Gamma Radiation from Solar Flares, Preprint and Astron. zh. (1964) (in press).

20 V. A. Ambartsumyan and G. S. Saakyan, Voprosy kosmogonii (Problems of Cosmogony) **9**, 91 (1963).

21 H. Y. Chiu, Ann. Phys. **26**, 364 (1964); H. Y. Chiu and E. E. Salpeter, Phys. Rev. Letts. **12**, 413 (1964).

22 A. Finzi, Astrophys. J. (1964) (in press).

23 Ginzburg, Ozernoĭ, and Syrovat-skiĭ, DAN SSSR **154**, 557 (1964), Soviet Phys. Doklady **9**, 3 (1964).

24 V. L. Ginzburg and S. I. Syrovat-skiĭ, On the Nature of Discrete X-ray Sources, DAN SSSR **158**, No. 4 (1964).

25 S. Hayakawa and M. Matsuoka, Proc. of the 4th Int. Space Science Symp. of COSPAR, 1963.

26 R. J. Gould and G. R. Burbidge, Astrophys. J. **138**, 969 (1963).

27 S. I. Nikol'skii, UFN **78**, 365 (1962), Soviet Phys. Uspekhi **5**, 849 (1963); Zatsepin, Nikol'skiĭ, and Khristiansen, Paper at the International Conference on Cosmic Rays, Jaipur, India, 1963.

28 Brook, Hayman, Kamiya, and Wolfendale, Nature **198**, 1293 (1963).

29 L. G. Dedenko and G. T. Zatsepin, JETP **40**, 630 (1961), Soviet Phys. JETP **13**, 439 (1961).

30 Baradzeĭ, Rubtsov, Smorodin, Solov'ev, and Tolkachev, Izv. AN SSSR ser. fiz. **26**, 575 (1962), Columbia Tech. Transl. p. 573.

31 Ganguli, Kameswara Rao, and Swami, Nuovo cimento **30**, 33 (1963).

32 V. L. Ginzburg and S. I. Syrovat-skiĭ, Proiskhozhdenie kosmicheskikh lucheĭ (Origin of Cosmic Rays), Moscow, AN SSSR, 1963. The English translation of this book (Pergamon Press, 1964) has been supplemented and revised.

33 F. B. McDonald and W. R. Webber, J. Phys. Soc. Japan **17**, Suppl. AII, 428 (1962).

34 Clark, Bradt, LaPointe, Domingo, Escobar, Murakami, Suga, Toyoda, and Hersil, Paper at International Conference on Cosmic Rays, Jaipur, India, 1963.

35 M. M. Komesaroff, Austr. J. Phys. **14**, 515 (1961).

36 Walsh, Haddock, and Schult, Proc. of the 6th Plenary Meeting of COSPAR, Warsaw, 1963.

37 J. A. Earl, Phys. Rev. Letts. **6**, 125 (1961).

38 V. L. Ginzburg and S. I. Syrovat-skiĭ, Astron. zh. **41**, 430 (1964), Soviet Astronomy **8**, 342 (1964).

[39] Firkowski, Gavin, Zawadski, and Maze, Nuovo cimento **29**, 19 (1963).

[40] Suga, Escobar, Clark, Hazen, Hendal, and Murakami, J. Phys. Soc. Japan **17**, Suppl. AIII, 128 (1961); Proc. Fifth Interamerican Seminar on Cosmic Rays, La Paz, Bolivia, **2**, 43 (1962).

[41] Vernov, Solov'eva, Khrenov, and Khristiansen, Paper at All-union Conference on Cosmic Ray Physics, Moscow, 1963.

[42] S. Hayakawa, Electrons and Photons in Primary Cosmic Rays, Preprint 1964.

[43] DeShong, Hildebrand, and Meyer, Phys. Rev. Letts. **12**, 3 (1964).

[44] J. B. Pollack and G. G. Fazio, Phys. Rev. **131**(6), 2684 (1963).

[45] S. A. Kaplan and S. B. Pikel'ner, Mezhzvezdnaya sreda (Interstellar medium), Fizmatgiz, 1963.

[46] P. H. Fowler and D. H. Perkins, Proc. Roy. Soc. **278**, 401 (1964).

[47] Yu. D. Kotov and I. L. Rozental', JETP **41**, 1411 (1962), Soviet Phys. JETP **16**, 1001 (1963).

[48] Baradzeĭ, Rubtsov, Smorodin, Solov'yev, and Tolkachev, Trudy, Physics Institute AN SSSR, v. 26, p. 224, 1964. Transactions of International Conference on Cosmic Rays, Jaipur, India, 1963.

[49] B. Rossi, High Energy Particles, New York, 1952.

[50] S. Z. Bilen'kiĭ, Lavinnye protsessy v kosmicheskikh luchakh (Cascade Processes in Cosmic Rays), Gostekhizdat, 1948.

[51] O. I. Dovzhenko and A. A. Pomanskiĭ, JETP **45**, 268 (1963), Soviet Phys. JETP **18**, 187 (1964).

[52] J. E. Felten and P. Morrison, Phys. Rev. Letts. **10**, 453 (1963).

[53] E. Feenberg and H. Primakoff, Phys. Rev. 73, 449 (1948).

[54] W. Heitler, The Quantum Theory of Radiation, Clarendon Press, Oxford, 1954.

[55] A. I. Nikishev, JETP **41**, 549 (1961), Soviet Phys. JETP **14**, 393 (1962).

[56] P. Goldreich and F. Morrison, JETP **45**, 344 (1963), Soviet Phys. JETP **18**, 239 (1964).

[57] S. E. Strom and K. M. Strom, Publ. Astron. Soc. Pacific **73**, 43 (1961).

[58] G. W. Clark and M. Oda, X-Ray Production in Super Nova Remnants, Preprint 1963.

[59] J. A. Northrop and R. L. Hostetler, Bull. Amer. Phys. Soc. **6**, 52 (1961).

[60] G. J. Perlow and C. W. Kissinger, Phys. Rev. **81**, 522; **84**, 572 (1951).

[61] J. F. Dolan and G. G. Fazio, The Gamma-Ray Spectrum of the Sun, Preprint 1964.

[62] V. L. Ginzburg and S. I. Syrovat-skiĭ, Astron. zh. **40**, 466 (1963), Soviet Astronomy **7**, 357 (1963).

[63] J. M. Kidd, Nuovo cimento **27**, 57 (1963).

[64] Duthie, Fowler, Kaddoura, Perkins, and Pinkau, Nuovo cimento **24**, 122 (1962).

[65] Chudakov, Dadykin, Zatsepin, and Nesterova, Trudy, Physics Institute Academy of Sciences USSR, v. 26, p. 118, 1964.

[66] Fruin, Jelley, Long, Porter, and Weekes, Phys. Letts **10**, 176 (1964).

[67] G. Cocconi, Proc. Moscow Conf. on Cosmic Rays II, 309 (1960).

[68] V. L. Ginzburg, DAN SSSR **156**, 43 (1964), Soviet Phys. Doklady **9**, 329 (1964).

[69] Bowyer, Byram, Chubb, and Friedman, Nature **201**, 1307 (1964).

[70] Giacconi, Gursky, Paolini, and Rossi, Measurements on Celestial X-Ray Sources, Communication Presented at the Fifth Intern. Space Sci. Symp., Florence, Italy, May 1964.

[71] D. W. Sciama, Cosmic X-Rays as a Tool for Exploring the Large-Scale Properties of Universe, Preprint, 1964.

[72] S. Hayakawa and M. Matsuoka, Possible Local Sources of Galactic X-Rays, Communication to the 8th Intern. Conf. of Cosmic Rays, Jaipur, India, 1963.

[73] D. C. Morton, Nature **201**, 1308 (1964).

[74] F. Hoyle, Astr. J. **137**, 993 (1963).

[75] Ginzburg, Ozernoĭ, and Syrovat-skiĭ, On Relativistic Electrons in the M82 Galaxy. Paper delivered at All-Union Conference on Cosmic-ray Physics (August 1964) (To be published in Izv. AN SSSR, ser. fiz.).

[76] H. Friedman, Sci. American **210**(6), 36 (1964).

[77] L. Woltjer, X-Rays and Type I Supernova Remnants, Preprint (1964).

[78] A. Finzi, The Cooling of a Neutron Star by the "Urca Process", Preprint (1964).

[79] V. L. Ginzburg and D. A. Kirzhnits, On the Superfluidity of Neutron Stars, JETP **47**, 2006 (1964), Soviet Phys. JETP, in press.

Translated by J. G. Adashko
44