Some aspects of gamma-ray astronomy

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The present state of gamma-ray astronomy is reviewed. The basic understanding of the processes by which gamma radiation is generated and absorbed is outlined. The basic observational results in various gamma-ray energy ranges are presented. The nature of the gamma bursts, the radiation source at the center of the local galaxy, etc., are discussed for the range of soft gamma-ray energies (below a few tens of megaelectron volts), where radiation in gamma lines is predominant. In the very high-energy range ($E_\gamma \gtrsim 10^{12}$ eV) and in the ultrahigh-energy range ($E_\gamma \gtrsim 10^{15}$ eV) of the gamma radiation, the discussion focuses on discrete sources, in particular, the enigmatic source Cygnus X-3. Most of the review is devoted to an analysis of the origin of cosmic rays on the basis of the existing gamma-ray data over the energy range from a few tens of megaelectron volts to several gigaelectron volts. The question of determining the cosmic-ray gradient from gamma-ray data, the generation of high-latitude gamma radiation, the problem of the gamma-ray halo of the local galaxy, etc., are discussed. Also discussed are some theoretical models which explain the nature of the unidentified gamma-ray sources. Theoretical predictions and the results of measurements of the flux of gamma radiation from the supernova SN1987A are discussed.

1. INTRODUCTION

Optical astronomy began to transform into an all-wavelength astronomy in 1931–33, upon the discovery of cosmic radio emission, as is well known. At first, the development of radio astronomy proceeded extremely slowly, and in addition the Second World War was an obstacle to scientific research. It was only after the end of the war, in 1945–46, that radio astronomy began to make rapid progress.[1] As a result of this progress, radio astronomy emerged a fairly long time ago as a mature branch of astronomy, generally enjoying the same status as optical astronomy. It is of course a rather difficult matter to compare astronomical research in different ranges; even in cases in which the radiation is coming from common entities, the different methods complement each other. In speaking of the maturity of radio astronomy, we thus have in mind the fact that radio-astronomy observatories have now been operating continuously for about 30 years, and in several regards the radio methods presently in use are strikingly sophisticated and diverse.

Putting aside research on the sun, we can say that x-ray astronomy was born in 1962 as a result of the unexpected discovery (in measurements carried out on a rocket) of intense x radiation from the source Sco X-1 (Scorpius X-1). In 1966 it was learned that this source is associated with a star (in other words, it was identified optically). From that point on, particularly after the 1970 launch of the special x-ray satellite Uhuru, an entire class of "x-ray stars" was observed, including pulsars in binary systems and other entities. On occasion (although extremely rarely), the term "x-ray stars" is also applied to discrete sources of a nonstellar nature, in particular, galaxies and quasars which are bright in the x-ray range. The development of x-ray astronomy proceeded rapidly, and to some extent this field became an independent and important branch of astronomy when the x-ray observatory Einstein was put into orbit in 1978 (Ref. 2). It is true that the need to carry out x-ray measurements outside the earth's atmosphere, i.e., on satellites and rockets, is still holding the scale of x-ray-astronomy research below that of optical or radial astronomy. However, even today there are several x-ray telescopes in continuous operation, and it is in large measure thanks to this circumstance that in August 1987 the Soviet extraterrestrial astrophysical observatory Kvant and the Japanese satellite Ginga were able to detect x radiation from the envelope of supernova SN1987A, which appeared on 23 February 1987 in the Large Magellanic Cloud.[3]

In gamma-ray astronomy, unfortunately, a completely different situation has arisen.

The possibilities of, and the outlook for, gamma-ray astronomy began to be discussed at least as far back as 1952 (Ref. 4); the first observations, made on balloons, were carried out in the 1960s.[5] The first gamma-ray satellite, OSOIII, was launched in 1968 (it is true that the gamma-ray satellite Explorer XI had been launched earlier, in 1961, and had managed to detect a few gamma rays). It was only in 1972–73, however, that a comparatively large amount of data (about 8000 gamma quanta were detected) was accumulated by the US gamma-ray satellite SAS-2 that operated for seven months. The year 1972 is also customarily regarded as the beginning of gamma-ray astronomy, at least at gamma-ray energies $E_\gamma \approx 30$–5000 MeV. In 1975 the European satellite COS-B was launched; it proved to be very successful and operated until 1982. The results obtained on this satellite and, to some extent, on SAS-2 are still being analyzed and discussed today. One reason is the wealth of data accumulated by COS-B over its seven years of operation. There is also another reason: the fact that since COS-B, down to the present day, no gamma-ray observatory has been in operation (!). Since the exceptional promise of gamma-ray astronomy is recognized quite well in the scientific world, this situation requires an explanation. Several circumstances have played a role here. The flux (in terms of the number of particles) of cosmic gamma rays is extremely small, at least at energies $E_\gamma > 30$ MeV. Specifically, a modern gamma-ray observatory must detect fluxes less than, or of the order of, 10^{-7} photon/cm$^2\cdot$s). We are thus talking about large installations and, correspondingly, fairly heavy satellites. Two such installations have been developed: the

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TABLE I. Gamma-Ray satellites intended for measurements at energies from tens of megaelectron volts to tens of gigaelectron volts.

Satellite (gamma-ray telescope)	GRASP (plan)	SAS-2	COS-B	Gamma (Gamma-I)	GRO (EGRET)	Gamma-400 (plan)
Energy range, MeV	0.3—100	30—200	70—5000	50—5000	20—30 000	5000—400 000
Period (or time) of operation	—	1972—1973	1975—1982	1989	1990	—
Duration of operation, yr	>2	0.6	6.5	~ 1—2	~ 2 (5)	~ 1
Mass, kg	1000	85	120	1500	1840	3000
Flux sensitivity, photon/(cm$^2\cdot$s)	$\sim 10^{-9}$	10^{-6}	$3\cdot 10^{-7}$	$\sim 10^{-7}$	$5\cdot 10^{-8}$	$\sim 10^{-10}$
Angular resolution	1′	$\sim 2.5°$	$\sim 2.5°$	20′—2°	1.6°	$\sim 1.6°$
Energy resolution $\Delta E_\gamma/E_\gamma$	$\gtrsim 0.001$	~ 0.5	~ 0.5	~ 0.5	0.15	~ 0.2
Time resolution, s	10^{-4}	$\sim 10^{-3}$	10^{-3}	10^{-3}	10^{-4}	$\sim 10^{-4}$

Soviet-French gamma-ray observatory Gamma and the US observatory GRO (The Netherlands and the Federal Republic of Germany are participating in this project). Data on the corresponding apparatus (taken from Ref. 6) are given in Table I. We immediately add that the launch of Gamma is, we hope, to take place in 1989, (but still significantly later than was originally proposed). The GRO was to have been put in orbit by a space shuttle, but the tragic accident involving one of the shuttles (the Challenger) in January 1986 has delayed the entire program for a long time. The net result is that the GRO will apparently be launched no earlier than 1990. The incident of the shuttle is of course an "objective difficulty," but in our opinion the delay of gamma-ray-astronomy research still reflects the inadequate recognition of the importance of this research on the part of the managers of the space programs and of science management in general. In particular, we cannot pin all our hopes on simply one or two gamma-ray observatories; it was possible and necessary to develop one or two more gamma-ray satellites, if only of the COS-B type, to be operated continuously. Whatever the case, we have not had any new observational results in the energy range $30 \leqslant E_\gamma \leqslant 5000$ MeV since 1982, and it may be several years more before we do.

Fortunately, no matter how important this range is, it does not hold a monopoly in gamma-ray astronomy: Observations are being carried out over the entire, very broad range of the gamma-ray spectrum from 10^5 eV up to about 10^{16} eV, i.e., ranging from hard x radiation[1)] up to the energies of particles which can be detected only by virtue of extensive air showers. Over a substantial part of this spectral range, something has already been accomplished, and more is presently being accomplished, so overall progress is continuously being made in gamma-ray astronomy. Over the entire 25-year existence of gamma-ray astronomy, however, only a few reviews on individual topics in this field have been published (Ref. 7, for example). We would also mention three monographs which discuss certain aspects of this field of astronomy.[8]

It is not our intention here to discuss the present state of gamma-ray astronomy as a whole. We instead focus on the relationship between cosmic gamma radiation and cosmic rays (by today's definition, "cosmic rays" are exclusively those charged particles of cosmic origin which have high energies). From this standpoint, the gamma-ray range above energies E_γ of say 30 MeV is particularly interesting. To complete the picture, however, we will also briefly discuss gamma-ray-astronomy questions which are not directly related to cosmic rays.

In §2 we offer a few comments characterizing the distinctive features of gamma-ray astronomy, and we present some results on the processes by which gamma radiation is generated. In §3 we discuss gamma-ray bursts and gamma-ray lines. In §4, which is the primary section of this review, we focus primarily on the energy range 30 MeV $\lesssim E_\gamma \lesssim 5000$ MeV. Here we are talking about the diffuse radiation of the local galaxy. In §5 we discuss the radiation from various discrete sources in this energy range. Finally, in §6 we discuss gamma radiation with energies $E_\gamma \gtrsim 10^{12}$ eV, which can be detected by virtue of the associated Cherenkov radiation (or "Vavilov-Cherenkov radiation") in the atmosphere and by virtue of the associated extensive air showers. In §7 we offer a few concluding comments primarily concerning the outlook for the further development of gamma-ray astronomy.

2. PROCESSES BY WHICH COSMIC GAMMA RADIATION IS GENERATED AND ABSORBED

Gamma rays are formed in a long list of processes. The most important of them for gamma-ray astronomy are the bremsstrahlung of relativistic electrons, the scattering of relativistic electrons by soft photons (i.e., the Compton effect or, as it is frequently called, the "inverse Compton effect"), synchrotron and curvature radiation, the decay of π^0 mesons, and, finally, the formation of gamma-ray lines as a result of nuclear transitions and certain other mechanisms. We will briefly discuss each of these processes below. We would like to insert a few general comments at this point so that we will not have to repeat them below.

Soft gamma radiation with a photon energy $E_\gamma \lesssim 1$ MeV can of course be generated by electrons with a kinetic energy $E_k \lesssim mc^2 = 0.5$ MeV. For the most part, however, we will be interested in ultrarelativistic electrons with a total energy $E \gg mc^2$. Such electrons, which are usually called simply "relativistic," will be the only electrons which we will discuss below. In this energy range, electrons and positrons are essentially on the same footing, so we will restrict the discussion to electrons. The bremsstrahlung of protons, which is produced as protons are scattered by protons or heavier nuclei, is weaker by a factor of at least $(M_p/m)^2 = 3.4\cdot 10^6$ than the bremsstrahlung of electrons (here $M_p = 1836m$ is of course the mass of a proton). In some cases, the bremsstrahlung of protons may nevertheless be of interest. Furthermore, in collisions with electrons protons may transfer a substantial momentum to the electrons. Such "δ-electrons" in turn generate bremsstrahlung, so the indirect contribution of protons to the radiation is greatly increased.[9] Furthermore, the radiation which accompanies the production of electrons and positrons in the decay $\pi^\pm \to \mu^\pm \to e^\pm$, for example, is similar in nature to bremsstrahlung (Subsection 2.2 below). With regard to the production of gamma rays in the decay of particles, the decay $\pi^0 \to 2\gamma$ is dominant, but not unique. We will not be discussing these and certain other processes, which play a secondary role. Even for the primary mechanisms, we will largely content ourselves with simply listing equations (see Ref. 10 for more details regarding the mechanisms for the emission of gamma radiation).

2.1. The quantities used in gamma-ray astronomy

In observations, one measures one of the following quantities: the intensity $J_\gamma(E_\gamma)$ or flux $F_\gamma(E_\gamma)$ in terms of the number of particles (in this case, photons) or the intensity $I_\gamma(E_\gamma)$ or flux $\Phi_\gamma(E_\gamma)$ in terms of the energy. We obviously have

$$I_\gamma(E_\gamma) = E_\gamma J_\gamma(E_\gamma),$$
$$F_\gamma(E_\gamma) = \int_\Omega J_\gamma(E_\gamma)\,d\Omega, \quad \Phi_\gamma(E_\gamma) = \int_\Omega E_\gamma J_\gamma(E_\gamma)\,d\Omega, \qquad (2.1)$$

where Ω is the solid angle.

The intensity J_γ is the number of particles which intersect a unit area in a unit solid angle per unit time, in a unit energy interval. The meaning of the other quantities is clear from (2.1). We will frequently make use of integral intensities, which are related to the differential intensities by

$$f(>E_\gamma) = \int_{E_\gamma}^{\infty} f(E'_\gamma)\,dE'_\gamma,$$

where f is any of the quantities which appear in (2.1).

We introduce the emissivity in terms of the energy, $\varepsilon_\nu \equiv \varepsilon(\nu)$, and that in terms of the number of photons, $q_\gamma(E_\gamma)$, where the radiation frequency $\nu = \omega/2\pi$ is related to the photon energy E_γ by

$$E_\gamma = h\nu = \hbar\omega. \qquad (2.2)$$

In turn, the relationship between the functions ε_ν and q_γ is given by

$$q_\gamma(E_\gamma) = \frac{\varepsilon_\nu\,d\nu}{E_\gamma\,dE_\gamma} = \frac{\varepsilon_\nu}{h^2\nu}. \qquad (2.3)$$

The radiation intensity J_γ is expressed in terms of the emissivity in the following way:

$$J_\gamma = \int_{\mathbf{l}} q_\gamma(E_\gamma, \mathbf{r})\,dr,$$
$$I_\gamma = \int_{\mathbf{l}} \frac{\varepsilon_\nu(\mathbf{r})}{h}\,dr, \qquad (2.4)$$

where the vector $\mathbf{l}$ specifies the direction along the line of sight ($\mathbf{r} = r\mathbf{l}$).

As we will show below, in several cases the gamma radiation is generated by various processes involving cosmic rays. In this case the function q_γ can be defined as

$$q_\gamma(E_\gamma, \mathbf{r}) = \int_{E_\gamma}^{\infty} P(E_\gamma, E, \mathbf{r})\,J_{cr}(E, \mathbf{r})\,dE; \qquad (2.5)$$

where P is the gamma-radiation spectrum generated by a charged particle with an energy E, and $J_{cr}(E,\mathbf{r})$ is the spectrum of cosmic rays at point $\mathbf{r}$.

If the generation of the gamma radiation is directly related to the interaction of cosmic rays with other particles (with a gas or with photons), the function $P(E_\gamma, E, \mathbf{r})$ can be put in the form

$$P(E_\gamma, E, \mathbf{r}) = n(\mathbf{r})\,\sigma(E, E_\gamma), \qquad (2.6)$$

where $n(\mathbf{r})$ is the density of particles whose interaction with cosmic rays leads to the generation of the gamma radiation, and $\sigma(E, E_\gamma)$ is the cross section for the given process. Using (2.4), (2.5), and (2.6), we can then write the following expression for the intensity of the gamma radiation:

$$J_\gamma(E_\gamma) = \int_{\mathbf{l}} dr\,n(\mathbf{r}) \int_{E_\gamma}^{\infty} dE\,\sigma(E_\gamma, E)\,J_{cr}(E, \mathbf{r}). \qquad (2.7)$$

Corresponding values for σ and P will be taken from Refs. 10f and 61a. The quantities $\tilde{q}_\gamma(E_\gamma)$ and $q_{1\gamma}(E_\gamma)$ are sometimes used in the literature. The emissivity $\tilde{q}_\gamma(E_\gamma)$ is used if the radiation is isotropic,

$$\tilde{q}_\gamma(E_\gamma) = 4\pi q(E_\gamma), \qquad (2.8)$$

while $q_{1\gamma}(E_\gamma)$ is the emissivity per gas atom (or per photon),

$$q_{1\gamma}(E_\gamma) = \frac{q(E_\gamma, \mathbf{r})}{n(\mathbf{r})}. \qquad (2.9)$$

For discrete sources (particularly with small angular dimensions), the following expression is customarily used for the flux:

$$F_\gamma(E_\gamma) = \int_\Omega J_\gamma(E_\gamma)\,d\Omega = \frac{1}{R^2}\int_V q_\gamma(E_\gamma)\,dV, \qquad (2.10)$$

where Ω is the solid angle subtended by the source, which has a volume V and which lies at a distance R from the observer.

2.2. Bremsstrahlung gamma radiation

Bremsstrahlung gamma radiation of relativistic electrons is generated when these electrons are scattered by nuclei or electrons of a neutral or ionized gas. When electrons are scattered by nuclei, the latter can be regarded as immobile, by virtue of the condition $M_p/m \gg 1$. For this reason, the nucleus acquires only momentum as a result of the interaction; its kinetic energy remains essentially constant. The energy of the scattered electron after its interaction with a nucleus is thus $E_2 = E_1 - E_\gamma$, where E_1 and E_2 are the initial and final energies of the electron, and E_γ is the energy of the photon which is produced. Under the conditions $(E_1, E_2) \gg mc^2$ the photons are emitted primarily along the direction in which the electron was originally moving, within an angle $\vartheta \sim mc^2/E_1$.

The electron scattering process results from long-range Coulomb forces, whose range ρ is determined by the screening. In a fully ionized gas, this radius is equal to the Debye length:

$$\rho \sim r_D = \left(\frac{kT}{8\pi ne^2}\right)^{1/2}.$$

In scattering by atoms, the charge of the nucleus is screened by the electrons of the atomic shells, with the result that the screening radius is determined by the dimensions of an atom:

$$\rho \sim a \sim \frac{\hbar^2}{me^2} Z^{-1/3}.$$

The screening efficiency is given by the parameter

$$\xi = \frac{r}{\rho}, \tag{2.11}$$

where r is the effective distance over which an electron with an energy E_1, passing by a nucleus of charge Ze, generates a gamma ray with an energy E_γ. Here (see, for example, Chap. 17 in Ref. 10f for more details)

$$r \sim \frac{\hbar}{mc} \frac{E_1(E_1 - E_\gamma)}{mc^2 E_\gamma}. \tag{2.12}$$

It is clear from expression (2.12) that the energy of the gamma ray which is radiated is higher, the closer the electron passes by the nucleus and, correspondingly, the smaller the screening parameter ξ.

The bremsstrahlung cross section $\sigma_{br}(E_\gamma, E)$ depends on how important the screening is.

In the ionized interstellar gas a Debye sphere is so large that screening can be ignored at essentially all electron energies; i.e., we have $\xi \gg 1$. The interaction cross section in this case is given by

$$\sigma_{br}(E_\gamma, E) = \frac{4e^2}{\hbar c} Z^2 \left(\frac{e^2}{mc^2}\right)^2 \frac{1}{E_\gamma} \left\{\left[1 + \left(1 - \frac{E_\gamma}{E}\right)^2\right]\Phi + \left(1 - \frac{E_\gamma}{E}\right)\Phi_2\right\}, \tag{2.13}$$

where

$$\Phi_1 = \ln\left(\frac{2E}{mc^2} \frac{E - E_\gamma}{E_\gamma}\right) - \frac{1}{2}, \quad \Phi_2 = \frac{2}{3}\Phi_1;$$

and the total cross section is (for $Z = 1$)

$$\sigma_{tot}(E) = \int_{E_\gamma} \sigma_{br}(E_\gamma, E)\, dE_\gamma \sim \frac{e^2}{\hbar c} \sigma_T, \tag{2.14}$$

where

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 = 6.65 \cdot 10^{-25}\ \text{cm}^2.$$

Expression (2.13) ignores the bremsstrahlung which arises in collisions with electrons of the medium. The effect of electron-electron collisions on cross section (2.13) can be dealt with crudely by replacing the factor Z^2 by $Z(Z+1)$. The meaning of this replacement is that the cross section for electron-electron collisions is roughly the same as that for electron-proton collisions. In a neutral medium there are Z electrons per atom with nuclear charge Ze.

For a neutral gas (hydrogen), under the usual conditions, with $E_\gamma/(E - E_\gamma) \sim 1$, the parameter ξ is

$$\xi = \frac{\hbar c}{e^2} \frac{mc^2}{E} \frac{E_\gamma}{E - E_\gamma} \sim 10^2 \frac{mc^2}{E}. \tag{2.15}$$

In this case the screening becomes important ($\xi \ll 1$) at electron energies $E \gg 50$ MeV.

It is clear from expressions (2.13) and (2.14) that the E dependence of the cross section $\sigma_{br}(E_\gamma, E)$ is weak, while the dependence on E_γ is determined by the factor $1/E_\gamma$ (furthermore, in the case of complete screening not only the factor Φ_2 but also Φ_1 is independent of E_γ). It is thus a fairly good approximation to write

$$\sigma_{br}(E_\gamma, E) = \frac{M}{t_{br} E_\gamma}, \tag{2.16}$$

where M is the mass of the atoms. For the radiation length unit t_{br} there are corresponding expressions, which are clear, in particular, from (2.13). For light elements, however, more-detailed calculations must be carried out (see, for example, Chap. 17 of Ref. 10f for these results). We would simply like to cite the value $t_{br} = 66\text{g/cm}^2$, which corresponds to the case of an un-ionized interstellar medium (consisting of about 90% H and about 10% He), for which we can set $M = 2 \cdot 10^{-24}$ g in (2.16).

Using expression (2.7), we can calculate the bremsstrahlung intensity along the direction **l** of interest, where $J_{cr}(E)$ must be taken to be the spectrum of cosmic electrons, $J_e(E)$, and where $n(\mathbf{r})$ must be taken to be the distribution of the gas density.

Using (2.16), for a neutral gas, we can thus write the following approximate expression for the bremsstrahlung intensity:

$$J_{\gamma\,br}(E_\gamma) \approx \frac{MN(L)}{t_{br}} \frac{J_e(>E_\gamma)}{E_\gamma} \approx 1.5 \cdot 10^{-2} M(L) \frac{J_e(>E_\gamma)}{E_\gamma}; \tag{2.17}$$

where L is a length scale of the gas-filled region along the line of sight, and

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

$$M(L) = MN(L),$$

$$J_e(>E_\gamma) = \int_{E_\gamma}^\infty J_e(E)\, dE.$$

It can be seen from expression (2.17) that the spectrum of gamma rays which are generated is similar to the original spectrum of electrons [in fact, for a power-law electron spectrum $J_e(E) = KE^{-\gamma}$ the bremsstrahlung intensity has the same dependence on the energy of the gamma rays:

$$J_\gamma(E_\gamma) \propto \frac{K}{\gamma - 1} \frac{E_\gamma^{-(\gamma-1)}}{E_\gamma} \propto E_\gamma^{-\gamma}$$

(do not confuse the γ specifying gamma radiation with the γ which is the spectral index of the electrons]. This result reflects the fact that the bremsstrahlung loss falls in the category of catastrophic losses; i.e., in most cases the energy of the resulting gamma ray is of the order of the initial energy of the electron which is scattered.

We conclude with one more generation mechanism: the formation of so-called polarization bremsstrahlung. This radiation arises in the collision of electrons and nuclei with multielectron atoms or with Debye spheres in a plasma, with the result that the screening shell goes into oscillation, and radiation is correspondingly generated. In contrast with the bremsstrahlung which we discussed above, polarization bremsstrahlung is generated equally efficiently by electrons and nuclei . Under certain conditions this may be the predominant type of radiation. However, the radiation generated by this mechanism lies for the most part at optical and x-ray frequencies, so this mechanism is not as important for the gamma radiation which is our subject here.[144]

2.3. The Compton effect

The Compton gamma radiation in which we are interested here arises in the scattering of relativistic electrons with an energy E by soft photons, with an energy $\varepsilon_{ph} \ll mc^2$. The nature of the process is determined by the dimensionless parameter

$$\eta = \frac{4E\varepsilon_{ph}}{(mc^2)^2}, \tag{2.18}$$

which is the ratio of the photon energy in the frame of reference in which the electron is at rest, $\varepsilon'_{ph} = \varepsilon_{ph}(E/mc^2)$, to the rest mass of the electron, mc^2. Under the condition $\eta \ll 1$ (i.e., under the condition $\varepsilon'_{ph} \ll mc^2$) an electron loses only a small portion of its energy in each collision with a photon. The cross section for this process is given by

$$\sigma(E_\gamma,\ \varepsilon_{ph},\ E) = \frac{1}{4}\pi\left(\frac{e^2}{mc^2}\right)^2 \frac{(mc^2)^4}{\varepsilon_{ph}^2 E^3}\left[2\frac{E_\gamma}{E} - \frac{(mc^2)^2 E_\gamma^2}{\varepsilon_{ph}E^3} + 4\frac{E_\gamma}{E}\ln\frac{(mc^2)^2 E_\gamma}{4\varepsilon_{ph}E^2} + \frac{8\varepsilon_{ph}E}{(mc^2)^2}\right]. \tag{2.19}$$

The energy of the gamma ray which is formed, E_γ, lies in the interval

$$\varepsilon_{ph} \leqslant E_\gamma \leqslant 4\varepsilon_{ph}\left(\frac{E}{mc^2}\right)^2.$$

The scattering of photons by moving electrons in this interval is classical, and the total cross section σ_{tot} is equal to the Thomson cross section

$$\sigma_{tot} = \int \sigma(E_\gamma,\ \varepsilon_{ph},\ E)\,dE_\gamma = \sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2. \tag{2.20}$$

The intensity of gamma radiation in direction $\mathbf{l}$ is given by (2.7), into which we must substitute the cross section for the process given above, in (2.19), and also the intensity of the cosmic-ray electrons and the distribution of photons. If there are photons with different energies (as there are, for example, in the local galaxy: optical, IR, and background), it is necessary to sum over the various contributions.

In the very simple case in which the electron intensity has an energy dependence $J_e(E) = KE^{-\gamma}$ and does not depend on the coordinates, we find from expression (2.7)

$$J_\gamma(E_\gamma) = \frac{1}{2} n_{ph} L K \sigma_T (mc^2)^{1-\gamma} \frac{4}{3} (\varepsilon_{ph})^{(\gamma-1)/2} E_\gamma^{-(\gamma+1)/2}, \tag{2.21}$$

where L is the length of the line of sight in the direction $\mathbf{l}$, and n_{ph} is the average density of photons along the line of sight.

We could also derive expression (2.21) from an approximate expression for the cross section for the process:

$$\sigma(E_\gamma,\ \varepsilon_{ph},\ E) = \sigma_T \delta\left(E_\gamma - \frac{4}{3}\varepsilon_{ph}\left(\frac{E}{mc^2}\right)^2\right). \tag{2.22}$$

It is clear from this expression that the average energy of the gamma ray which is produced is

$$E_\gamma \approx \frac{4}{3}\varepsilon_{ph}\left(\frac{E}{mc^2}\right)^2. \tag{2.23}$$

For estimates we can also use the expression

$$J_\gamma(E_\gamma) = \frac{\sqrt{3}}{4} n_{ph} L \sigma_T \frac{mc^2}{(\varepsilon_{ph}E_\gamma)^{1/2}} J_e(E), \tag{2.24}$$

where E_γ, ε_{ph}, and E are related by (2.23).

At a parameter value $\eta \gg 1$, the nature of the process changes. The loss becomes catastrophic (by which we again mean that in an individual collision with a photon an electron ordinarily loses a substantial fraction of its energy), and the cross section for the process decreases sharply. The total cross section for scattering in this case is given by

$$\sigma_{tot} = \frac{3}{8}\sigma_T \frac{(mc^2)^2}{E\varepsilon_{ph}}\left(\ln\frac{2\varepsilon_{ph}}{mc^2} + \frac{1}{2}\right) \leqslant \sigma_T. \tag{2.25}$$

In most cases encountered in astrophysics, however, the scattering of electrons by photons is described by expression (2.19). To demonstrate this point, we note that the condition $\eta \ll 1$ which we mentioned above [see (2.18)] takes the form

$$E \ll \frac{1}{4} mc^2 \frac{mc^2}{\varepsilon_{ph}} \approx \frac{6\cdot 10^{10}}{\varepsilon_{ph}\ (\text{eV})}\ \text{eV}. \tag{2.26}$$

Even in the scattering of electrons by optical photons ($\varepsilon_{ph} \sim 1$eV, requirement (2.26) means $E \ll 10^{11}$ eV.

2.4. Synchrotron radiation and curvature radiation

Synchrotron radiation is generated by relativistic electrons as they move in magnetic fields. As in Compton radiation, energy is lost in small portions in the course of synchrotron radiation. The radiation which is generated propagates along the direction in which the electron is moving; most of the radiation is within an angle $\vartheta \lesssim mc^2/E$.

The spectrum radiated by an individual electron, $P(\nu)$, is given by

$$P(\nu) = \frac{\sqrt{3}e^3}{mc^2} H_\perp \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\,d\eta, \tag{2.26'}$$

where ν is the frequency of the radiation, $H_\perp$ is the component of the magnetic field perpendicular to the line of sight, and $K_{5/3}(x)$ is the modified Bessel function. The characteristic frequency ν_c in (2.26') is

$$\nu_c = \frac{3}{4\pi}\frac{eH_\perp}{mc}\left(\frac{E}{mc^2}\right)^2. \tag{2.27}$$

The electron radiation function $P(\nu)$ reaches a maximum at the frequency

$$\nu_m \approx 0.29\nu_c = 4.6\cdot 10^{-6} H_\perp(\text{Oe})\, E^2\ (\text{eV}),$$
$$E_m = h\nu_m = 1.9\cdot 10^{-20} H_\perp\ (\text{Oe}) E^2\ (\text{eV}).$$

It can be seen from this expression that gamma rays with energies $E_\gamma = h\nu > 0.1$ MeV can be generated by the synchrotron mechanism only under fairly specific conditions. For example, photons with an energy $E_\gamma > 0.1$ MeV are generated in fields $H \gtrsim 10^3$ Oe if there are electrons with energies $E \gtrsim 10^{11}$ eV, i.e., only in the atmospheres of certain stars, and then only if electrons with a very high energy are generated.

The intensity of the synchrotron radiation in the direction $\mathbf{l}$ is given by (2.4) and (2.5), and the function $P(\nu)$ has the form in (2.26).

While the intensity of electrons in a volume under consideration is constant and is a power function of the energy of the particles, i.e., if

$$J_e(E) = KE^{-\gamma},$$

the intensity of the gamma rays is given approximately by

$$J_\gamma(E_\gamma) = 0{,}79a(\gamma)LKH_\perp^{(\gamma+1)/2} \times \left(\frac{2{,}59\cdot10^4}{E_\gamma}\right)^{(\gamma+1)/2} \text{photon/cm}^2\cdot\text{s}\cdot\text{sr}\cdot\text{eV} \tag{2.28}$$

here L is a length scale of the radiating region, the number $a(\gamma)$ is approximately 0.5 at $\gamma = 1.5°$, and in general we would have $a(\gamma) \sim 0.1$. In (2.28), E is expressed in electron volts, $H_\perp$ in oersteds, and K in erg$^{\gamma-1}$/cm^3. In deriving (2.28) we can use the approximate expression for the spectral power of the radiation, $P(\nu)$, in the case of an isotropic electron distribution:

$$P(\nu) = P\delta(\nu - \nu_m),$$

where P is the total power of the magnetobremsstrahlung, given by

$$P = \frac{2e^4H_\perp^2}{3m^2c^3}\left(\frac{E}{mc^2}\right)^2.$$

It is clear from (2.28) that there is a relationship between the intensity of the magnetobremsstrahlung and the intensity of relativistic electrons:

$$J_\gamma(E_\gamma) \propto LJ_e(E). \tag{2.29}$$

The relationship between E and E_γ here is found from (2.27).

A characteristic feature of synchrotron radiation is that it is polarized in an ordered magnetic field. For a power-law isotropic electron spectrum $J(E) = KE^{-\gamma}$, for example, the degree of linear polarization in a uniform magnetic field is

$$\Pi_0 = \frac{\gamma+1}{\gamma+(7/3)}.$$

The generation of synchrotron radiation by neutron stars with magnetic fields $H \gtrsim 10^{12}$ Oe is a quantum-mechanical process. It has several distinguishing features (Refs. 148):

- large relative components of various harmonics,
- transitions between levels with spin flip and thus a pronounced depolarization of the radiation,
- recoil effects (subsection 2.6).

An important point is that the characteristics of the radiation depend strongly on the relation between the time scales which determine the generation of synchrotron photons in this case. For example, one distinguishes between "steady-state synchrotron radiation" and "synchrotron cooling radiation," depending on the relation between the lifetime of the excited state and the excitation time.

The "curvature radiation" or "magnetodrift radiation" is analogous to synchrotron radiation.[10d,f] This radiation arises in the magnetospheres of neutron stars, where the magnetic fields reach 10^{11}–10^{13} Oe.

In a nonuniform ("curved") field, a charge drifts in the direction perpendicular to the plane of a field line. As a result, a Lorentz force arises and curves the trajectory of the particle; in a first approximation we can thus say that the charge is moving along a curved field line with a radius of curvature R_c. Using the corresponding expressions for synchrotron radiation, (2.26) and (2.27), we can derive expressions for the characteristic frequency of curvature radiation and for the spectral and total power radiated by the particle[10d]:

$$\nu_c = \frac{3}{4\pi}\frac{c}{R_c}\left(\frac{E}{mc^2}\right)^3,$$

$$P_\nu = \frac{\sqrt{3}}{2\pi}\frac{e^2}{R_c}\frac{E}{mc^2}\frac{\nu}{\nu_c}\int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\,d\eta,$$

$$P = \int P_\nu\,d\nu = \frac{2}{3}\frac{e^2c}{R_c^2}\left(\frac{E}{mc^2}\right)^4 \tag{2.30}$$

(in this case, the curvature of the field line, R_c, is serving as Larmor radius). The curvature radiation which is generated in strong ordered magnetic fields is like synchrotron radiation in that it is polarized. Several models (Subsection 5.3) link the gamma radiation from pulsars with synchrotron radiation or curvature radiation of electrons. In this connection it is interesting to note that there are indications that the gamma radiation from the Vela pulsar which was detected on the COS-B satellite is polarized, with a degree of polarization close to 100%. (Ref. 11). If this result were to be confirmed, the meaning would be that polarized radiation in the gamma-ray range has been observed for the first time.

2.5. Decay of π^0 mesons and similar decays

The generation of gamma rays results from collisions of cosmic-ray protons and other nuclei with protons and other nuclei of the interstellar gas. These nuclear reactions are accompanied by the production of π^0 mesons and Σ^0 hyperons, which rapidly decay, in a process in which gamma rays are formed. In addition to the direct production of π^0 mesons, these mesons are also produced in nuclear collisions through the decay of various mesons and hyperons: $K^\pm \to \pi^\pm + \pi^0, \Lambda \to n + \pi^0$, etc. The result is again the emission of gamma rays.

With a branching ratio of 98.8%, the decay of the π^0 meson goes by the mechanism $\pi^0 \to 2\gamma$. The energy of the gamma rays from the decay of a π^0 meson at rest is thus usually $E_\gamma = (1/2)m_\pi c^2 = 67.5$ MeV.

The branching ratios and kinetics of all of the corresponding reactions are known quite well,[10d,12] so the gamma-ray spectrum can be calculated. We also note that nuclear reactions such as (pp), (pα), and (αp) result in the production of roughly equal numbers of π^0, π^+, and π^- mesons. The decays of any of these particles may lead to the production of gamma rays: $\pi^0 \to \gamma\gamma$, $\pi^\pm \to \mu^\pm \to e^\pm \gamma\nu\bar{\nu}$. As we have already mentioned, however, the branching ratio for the decay of a π^0 meson into two gamma rays is nearly 100%. On the other hand, the decay of a $\mu^\pm$ meson occurs primarily by the mechanism $\mu^\pm \to e^\pm \nu\bar{\nu}$, i.e., without the production of a gamma ray. The branching ratio for the decay by the mechanism $\mu^\pm \to e^\pm \gamma\nu\nu$ (which is none other than the bremsstrahlung of a secondary electron) contains an additional factor of $e^2/hc = 1/137$, in accordance with the expressions for bremsstrahlung. Consequently, the intensity of the gamma rays accompanying the decay of $\pi^\pm$

mesons is two orders of magnitude lower than the intensity of the gamma rays emitted in the decay of a π^0 meson.

The intensity of the gamma radiation from the decay of π^0 mesons in a certain direction **l** is thus given by expression (2.7), where $n(\mathbf{r})$ is the gas distribution in the local galaxy, and J_{cr} is the intensity distribution of the proton-nucleus component of the cosmic rays.

If gas and cosmic rays fill a volume of space with a length scale L with a constant density, the intensity of the gamma radiation at sufficiently high energies can be described approximately by (here we are making use of the relationship $E_\gamma \sim E$)

$$J_\gamma(E_\gamma) \approx n_H L J_{cr}(E). \qquad (2.31)$$

Knowing the spectrum and composition of the cosmic rays, we can estimate the emissivity q_γ of the local galaxy near the earth (see the corresponding data in, for example, §18 of Ref. 10f). This emissivity is usually expressed per 1 cm^3 or per hydrogen atom [see (2.5) and (2.9)].

The results of one version of calculations of this sort[12a] are shown in Fig. 1. This is a plot of the gamma-ray emissivity for the gamma rays produced both by the proton component through the production of π^0 mesons and by the electron component through the bremsstrahlung loss. It can be seen from Fig. 1 that for the cosmic-ray spectrum observed at the earth the gamma radiation associated with the gas is formed at energies $E_\gamma > 200$–300 MeV through the production of π^0 mesons, while at lower energies this radiation is formed primarily through an electron bremsstrahlung.

2.6. Generation of gamma lines

Gamma-ray astronomy in lines opens up some extensive opportunities for directly studying a long list of problems in nuclear space physics. Among these problems are studying the soft cosmic rays or, as they are sometimes

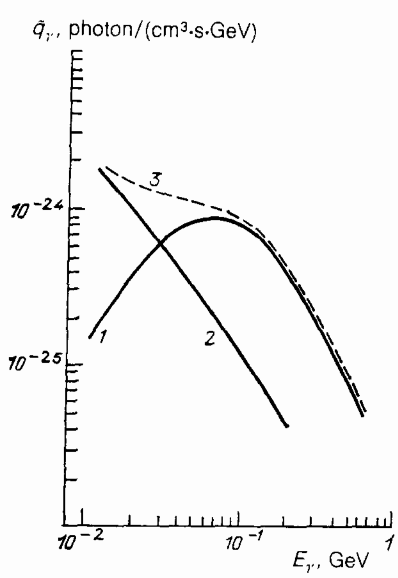

FIG. 1. Gamma-ray emissivity in the local galactic neighborhood.[12a] 1—Gamma rays formed through the decay of π^0 mesons; 2—gamma rays formed through the bremsstrahlung loss of relativistic electrons (the electron spectrum at energies $E \lesssim 1$ GeV was found from radio data); 3—resultant emissivity of the local galactic volume in the gamma range.

called, subcosmic rays with energies $E < 100$ MeV, studying gas and dust clouds, directly observing nuclear fusion in novae and supernovae, and studying processes at the surface of neutron stars. We now have a substantial body of theoretical and experimental data on this question (see the reviews[7a,c]). Here we will discuss only the processes by which gamma-ray lines are generated in galactic and metagalactic objects; we will not discuss the extremely important question of the generation of gamma radiation in solar flares (see, for example, the reviews in Refs. 7c and 13 regarding gamma-ray lines in solar flares).

Let us briefly characterize the individual gamma-ray lines.

2.6.1. Cyclotron line

The radiation in this line is formed by electrons of comparatively low energy which are being acted upon by magnetic fields. The radiation frequency is given by the following expression if we ignore relativistic corrections:

$$\omega_H \approx \frac{eH}{mc} \approx 1.76 \cdot 10^7 H. \qquad (2.32)$$

It is clear from (2.32) that cyclotron radiation falls in the gamma-ray range if the magnetic fields are sufficiently strong. For example, we would have $E_\gamma = \hbar\omega_H \sim 0.1$ MeV at $H \sim 10^{13}$ Oe.

Magnetic fields of this strength are characteristic of the magnetospheres of neutron stars. It should be kept in mind here that in sufficiently strong magnetic fields the radiation cannot be regarded as classical. It acquires some substantially quantum-mechanical features.

We are talking about the quantum-mechanical frequency correction for the "recoil effect"—the change in the frequency of radiation due to the change in the longitudinal momentum and transverse energy of the electron during the emission of a photon. In the strong magnetic fields of neutron stars, the parameter which characterizes the recoil effect, $\hbar\omega/mc^2$, can reach a substantial level: of the order of 0.1. Furthermore, in strong magnetic fields, in which the plasma becomes quantized, with $\hbar\omega \gg kT$ (T is the plasma temperature), the radiation at frequencies $\omega \sim \omega_H$ acquires a quantum-mechanical nature (we are dealing with the Wien limit $\hbar\omega \gg kT$). Corresponding expressions describing cyclotron radiation in the magnetosphere of a neutron star are given in Ref. 14.

If a system of particles radiates, it is also capable of absorbing this radiation. It is thus clear that not only cyclotron gamma-ray lines in emission (an intensity excess) but also cyclotron gamma-ray lines in absorption (an intensity deficiency) can form in the emission spectra of neutron stars.

2.6.2. Annihilation electron-positron line ($e^+ + e^- \to \gamma + \gamma$)

Under the conditions prevailing in space, positron production is a fairly common phenomenon. For example, positrons appear in the β^+ decay of nuclei, in the generation of electron-positron pairs (in the magnetospheres of neutron stars), in the decay $\pi^+ \to \mu^+ \to e^+$, and in several other processes. A distinction should be drawn between the in-flight annihilation of relativistic or at any rate fast positrons and the annihilation of positrons which are at rest (or moving slowly). In the former case, a continuous or at least extreme-

TABLE II.

Decay chain	Decay time, yr	Energy of gamma line, MeV
$^{56}Ni \to {}^{56}Co \to {}^{56}Fe^*$	1.07	0.847; 1.24 etc.
$^{57}Co \to {}^{57}Fe^*$	11	0.122
$^{22}Na \to {}^{22}Ne^*$	38	1.275
$^{44}Ti \to {}^{44}Sc \to {}^{44}Ca^*$	68	1.156
$^{26}Al \to {}^{26}Mg^*$	$1.1 \cdot 10^6$	1.809

*Excited nucleus

ly broad spectrum is formed (Ref. 15, for example). In the latter case (the annihilation of stopped positrons) the gamma radiation is monochromatic ($E_\gamma = mc^2 = 0.51$ MeV) and can in principle be distinguished from the background continuous spectrum by virtue of this monochromaticity.

Annihilation in the strong magnetic field of a neutron star has some distinctive features:

- Single-photon annihilation becomes predominant.
- The radiation may be strongly polarized.

The reader interested in more details on this topic is directed to Ref. 148b and the bibliography there.

2.6.3. Gamma-ray lines from nucleosynthesis processes

According to the present understanding, the primary sources of the production of most elements are processes which occur in stars. The nucleosynthesis in the local galaxy is linked primarily with the explosions of supernovae and novae, with processes which occur in O stars and Wolf-Rayet stars, and with pulsating red giants. Generally speaking, the formation of new elements can be detected by methods of gamma-ray astronomy. The idea here is that the radioactive elements which are produced in the course of nucleosynthesis processes would undergo decays accompanied by the appearance of gamma rays (a gamma ray would be radiated by an excited nucleus which is formed).

Table II lists some gamma-ray lines which may be characteristic of the local galaxy. In all these examples the gamma ray is emitted by the last nucleus in the chain (e.g., ^{56}Fe) which is formed in an excited state.

2.6.4. Gamma-ray lines generated by cosmic rays

Excited nuclei can also form in the interaction of cosmic rays with interstellar gas or dust (these nuclei would be either nuclei involved in the interaction or their products). The transitions of these nuclei to lower-lying states would be accompanied by the emission of a gamma ray, as in the preceding case.

TABLE III.

Gamma-ray energy, MeV	Nuclear reaction
0.847	^{56}Fe (p, p′) ^{56}Fe*
1.634	^{24}Mg (p, x) ^{20}Ne*
4.238	^{12}C (p, p′) ^{12}C*
6.126	^{16}O (p, p′) ^{16}O*

In principle, there could be various versions of the transition. Below we cite the gamma-ray energies corresponding to the most probable version. If the excited nuclei are at rest, a line should be observed in the spectrum. If the transition to the ground state instead occurs in nuclei in rapid motion, an emission band will form in the spectrum.

Table III lists some emission lines or bands which may be manifested in the diffuse galactic spectrum.

Figure 2 (Ref. 16) shows an example of the spectrum of the diffuse gamma radiation for the interstellar medium of the local galaxy. In this spectrum there are three components of the emission in lines:

1. Broad bands emitted by fast excited nuclei with energies of the order of several MeV/nucleon and above (e.g., the ^{12}C line).

2. An emission in narrow lines by nuclei which have an energy of no more than a few tens of keV/nucleon after the collisions.

3. Very narrow lines emitted by nuclei whose decay time is so long that they come to a stop before they revert to

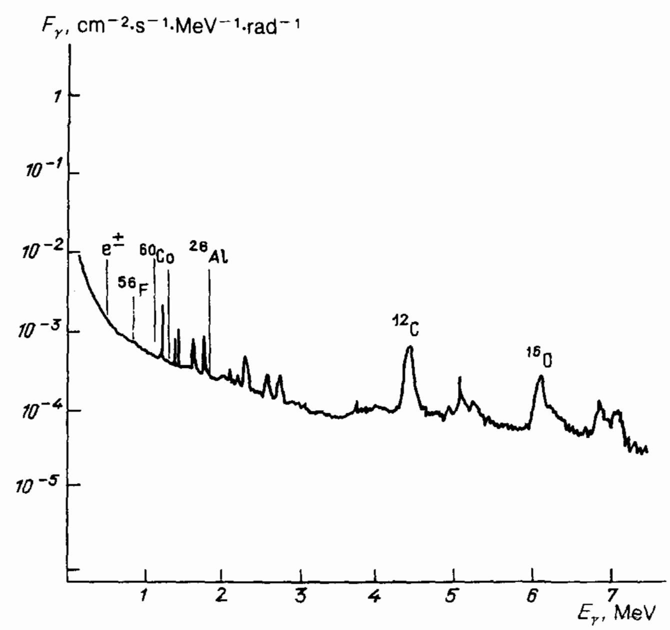

FIG. 2. Line emission of galactic interstellar space (calculated results[16]). The lines from radioactive nuclei produced in a nucleosynthesis process (^{60}Co and ^{26}Al) and also the gamma lines resulting from the interaction of cosmic rays with the interstellar gas and dust have been taken into account.

the ground state. In particular, narrow lines of this sort may be generated by dust nuclei if the dust particles are sufficiently large ($> 10^{-4}$ cm) and the decay time is sufficiently long ($> 10^{-12}$ cm).

2.6.5. *Exotic gamma-ray lines*

Gamma-ray lines may also arise in the course of the annihilation of matter and antimatter[17] and in the decay or annihilation of hypothetical slow supersymmetric particles of cosmological origin.[18] Such particles are sometimes linked with the dark matter in both the local galaxy[19] and metagalactic space.[18]

The presence of supersymmetric particles in space could in principle be detected on the basis of the gamma-ray lines which arise in the course of the annihilation of these particles. The energy of these gamma-ray lines would be in the range 1–10^3 GeV (Ref. 20), since these supersymmetric particles would have to have the energies corresponding to their rest masses.

2.7. Absorption of gamma rays

The most important processes by which gamma rays are absorbed in galactic space are the following[10f]:

1. Compton scattering.[2)]
2. The production of e^+e^- pairs in a medium.
3. The production of e^+e^- pairs on thermal and, in general, "soft" photons (the process $\gamma + \gamma' \rightarrow e^+ + e^-$, where γ' is a soft photon).
4. Absorption by nuclei (the nuclear photoeffect and the excitation of nuclei).
5. The production of π^+ and π^- mesons on protons and nuclei. The production of other particles.
6. In a sufficiently strong magnetic field, a possible efficient production of $e^+ + e^-$ pairs by a photon and its possible splitting into two photons.

We might also mention the ionization of atoms, transitions in the continuous spectrum, and transitions between atomic levels, but these processes are important only in the softer (x-ray) region. Compton absorption is the dominant process for gamma rays with energies $E_\gamma > 50$ keV and up to an energy $2mc^2 = 1$ MeV, at which $e^+ + e^-$ pairs begin to form. At $E_\gamma < mc^2$ the total scattering cross section is roughly equal to the Thomson cross section: $\sigma_c = \sigma_T = 6.65\cdot 10^{-25}$ cm^{-2}. With increasing energy (at $E_\gamma \gg mc^2$) the Compton cross section decreases [see (2.25)]. At $E_\gamma = 10^3\, mc^2$, for example, we have $\sigma_c = 3\cdot 10^{-3}\sigma_T$.

At $E_\gamma \lesssim mc^2$ the absorption coefficient for gamma radiation, μ_c, in the interstellar medium is

$$\mu_c = \sigma_T n_e = 6{,}65\cdot 10^{-25} n_e \text{ cm}^{-1}, \qquad (2.33)$$

where n_e is the total density of all electrons in the medium [the radiation intensity decreases over a distance r in accordance with $J(r) = J_0 e^{-\mu r}$].

Compton absorption is dominant at energies $E_\gamma < 10^8$ eV. At higher energies, pair production becomes more important.

In a neutral gas, pair production occurs in a first approximation under conditions of complete screening. The corresponding expression for the interstellar medium is

$$\mu_{\text{pair}} = 2\cdot 10^{-26} n_a \text{ cm}^{-1}, \qquad (2.34)$$

where n_a is the density of atoms.

In a plasma, in the cases of interest here, screening can be ignored, and we can write

$$\mu_{\text{pair}} = \frac{4e^2 Z(Z+1)}{\hbar c}\left(\frac{e^2}{mc^2}\right)^2 n_a\left(\frac{7}{9}\ln\frac{2E_\gamma}{mc^2} - \frac{109}{54}\right)$$

$$= 3.6\cdot 10^{-27}\left(\ln\frac{E_\gamma}{mc^2} - 1.9\right) n_a \text{ cm}^{-1}. \qquad (2.35)$$

At even higher energies of the gamma rays, pair production on thermal photons becomes an important process. In a frame of reference in which the total momentum of the two photons is zero, pair production begins at an energy[3)] $E'_\gamma = mc^2$. In the laboratory frame, in which we have a gamma ray with an energy E_γ and a thermal photon with an energy ε_{ph}, the production threshold corresponds to an energy

$$E_{\gamma,0} = \left(\frac{mc^2}{\varepsilon_{\text{ph}}}\right) mc^2 = 5\cdot 10^5\left(\frac{mc^2}{\varepsilon_{\text{ph}}}\right) \text{ eV}. \qquad (2.36)$$

For optical photons ($\varepsilon_{\text{ph}} \sim 1$ eV) this energy is $E_{\gamma,0} \approx 2\cdot 10^{11}$ eV. For photons of the metagalactic background radiation ($T = 2.7$ K, $\varepsilon_{\text{ph}} \sim 10^{-3}$ eV), the value of $E_{\gamma,0}$ is of the order of $2\cdot 10^{14}$ eV.

The absorption coefficient corresponding to optical photons reaches a maximum at $E_\gamma = 10^{12}$ eV:

$$\mu_{\max} = 7\cdot 10^{-12} w_{\text{ph}} \text{ cm}^{-1}, \qquad (2.36')$$

where w_{ph} is the energy density of the optical photons, in units of electron volts per cubic centimeter (for a slightly more detailed discussion, see Ref. 10f).

The absorption by photons of the background radiation is stronger by yet another 1.5 orders of magnitude, but it reaches its maximum only at $E_\gamma \sim 10^{15}$ eV.

What are the optical thicknesses $\tau = \mu R$ for gamma rays of various energies in the local galaxy? As a typical size of the galaxy we take R to be 10 kpc $= 3\cdot 10^{22}$ cm. We set the average gas density in the galactic disk equal to $n_a \approx 1$ cm^{-3}, we take the energy density of optical photons to be $w_{\text{ph}}^{(0)} \approx 1$ eV/cm^3, and we take the energy density of the background-radiation photons to be $w_{\text{ph}}^{(r)} \approx 0.3$ eV/cm^3. We then find Table IV.

The values used here mean that we are talking about maximum absorption, since the density n_a and the density $w_{\text{ph}}^{(0)}$ both decrease with distance from the disk.

2.8. Distinctive features of the galactic gamma radiation

One of the distinctive and also attractive features of the gamma-ray range is that essentially the entire galaxy is transparent to gamma rays, as can be seen from Table IV. Only at energies $E_\gamma \sim 10^{15}$–10^{16} eV is the optical thickness roughly equal to the size of the local galaxy. In this connection, gamma-ray astronomy makes it possible to study various objects in the local galaxy which are inaccessible to observations in other wavelength ranges.

Furthermore, the gamma radiation is of a nonthermal nature for the most part; i.e., the gamma rays in the local galaxy form in processes involving high-energy particles. As a result, the intensity of the corresponding component of the gamma radiation is proportional to the intensity of cosmic rays, and—a particularly important point—a large fraction of the gamma radiation of the local galaxy is associated with the proton-nucleus component of the cosmic rays. It is thus

TABLE IV.

Gamma-ray energy, MeV	Absorption process	Optical thickness
$5\cdot10^4-5\cdot10^7$	Compton scattering	$2\cdot10^{-2}$
$5\cdot10^8-10^{11}$	Production of e^+e^- pairs in a medium	10^{-3}
$5\cdot10^{11}-5\cdot10^{13}$	Production of e^+e^- pairs on optical photons	10^{-3}
$2\cdot10^{15}$	Production of e^+e^- pairs on background-rad'n photons	1.4
10^{16}	Production of e^+e^- pairs on background-rad'n photons	0.78
10^{17}	» »	0.14

clear that it is in specifically the gamma-ray range that we can obtain information about the distribution of the densities of cosmic-ray protons and nuclei in the local galaxy.

3. DISCRETE SOURCES OF SOFT GAMMA RADIATION

We turn now to the characteristics of the radiation and to models of several galactic and extragalactic gamma sources, whose spectra lie for the most part at energies $E_\gamma < 30$ MeV. As might be expected on the basis of the discussion above (Subsection 2.6), it is in this energy range that we would naturally expect to see several features associated with the generation of gamma-ray lines. The existence of such features in the observed spectra provides a unique opportunity for determining the mechanisms for the radiation by the sources of interest. We might mention Ref. 150 as a recent reference on these questions.

3.1. Gamma bursts

Over the past 15 years, research on gamma bursts has emerged as an independent and interesting field of space research, with an abundance of experimental data and a total lack of understanding of the nature of the sources of these bursts. Some distinguished research results on gamma bursts have been obtained in the USSR by the group led by Mazets (the Konus experiment, carried out on the Venera interplanetary probe) and also in the Soviet-French experiment Sneg on the Venera interplanetary probe and the Prognoz-9 satellite. Many tens of gamma burst have already been detected in the Soviet-French experiment carried out on the Fobos probes.

Gamma bursts were discovered by chance in 1967 on the Vela satellites, which were designed for detecting man-made nuclear explosions in space (see the reviews in Refs. 7a, 8, and 21 regarding gamma bursts). Gamma bursts are seen as a sporadic and rare increase in the intensity in an unpredictable part of the sky. The energy interval in which the gamma bursts are radiated stretches from a few tens of kiloelectron volts to several megaelectron volts (in one case, it was found possible to detect radiation up to 30 MeV; Ref. 22). The time-integrated energy flux of the radiation arriving at the earth has values up to $\sim 10^{-3}$ erg/cm^2, but most of the bursts are considerably weaker. On the average, several gamma bursts (with a flux $>10^{-7}$ erg/cm^2 occur in the course of a day. Their temporal profile has an extremely complex multicomponent structure.[23] For certain bursts one observes a sharp increase in intensity over a time scale $t \lesssim 2\cdot10^{-4}$ s, followed by decay of the intensity. The total duration of the bursts ranges from 0.1 to 100 s. The gamma bursts which have been detected are distributed isotropically over the celestial sphere. The dependence of their number on the measured flux, however, rules out the possibility of a uniform spatial distribution of the sources of the bursts.[24] The density of the sources of the observed gamma bursts appears to fall off with distance from the earth, but we cannot rule out the possibility that this decrease is an instrumental effect (a selection effect).[21c,146]

Two possibilities for the origin of gamma bursts are being discussed.

a) The sources of the gamma bursts lie relatively close to the earth (at distances $\lesssim 1$ kpc). In this case we would be forced to assume that these sources lie in the galactic disk, that they have a thickness of a few hundred parsecs, and that their energy evolution W does not exceed about 10^{39} erg.

b) The sources of the gamma bursts are far from the earth. The distance to them is of the order of 100 kpc (Ref. 25). In this model the energy release by the sources is large: It must reach 10^{44} erg.

One of the primary questions of course is the nature of the radiation in the gamma bursts. In this connection, the sources of gamma bursts occupy a special place among sources of gamma radiation, since the accuracy with which their angular coordinates can be determined is the best in gamma-ray astronomy. The coordinates of the most intense gamma bursts can be measured within a fraction of an arc minute. However, the situation is peculiar in that in nearly all cases the regions from which the bursts are observed are "empty." In other words, no specific sources of optical, radio, or x radiation are observed there with which the gamma bursts could be identified.

In only one case has it been found possible to detect the envelope of a supernova within the "error box" of a gamma burst. This was the famous gamma burst which was observed on 5 March 1979. Since this envelope was in the Large Magellanic Cloud galaxy, at a distance of 55 kpc from the earth, we are obliged to assume that the energy released in the burst was 10^{44} erg (if the coincidence of the envelope and the burst on the celestial sphere was not simply by chance).

There is a widespread opinion that the gamma bursts are associated with neutron stars. The strongest evidence for this interpretation has been found from a study of spectral characteristics.[21b] Two features are sometimes observed in the spectrum of gamma bursts, one constituting a radiation "deficit" at an energy $E_\gamma \lesssim 100$ keV, and the other being a radiation "excess" at an energy $E_\gamma \gtrsim 400$ keV. Some typical spectra are shown in Fig. 3. It is usually assumed that the first line is a cyclotron absorption line in the magnetic field of a neutron star, with $H \approx 5\cdot10^{12}$ Oe (but see Ref. 26), while the other line is the 511-keV e^+e^- annihilation line, red-shifted by the gravitational field of a neutron star.

These features have been observed in a fairly large num-

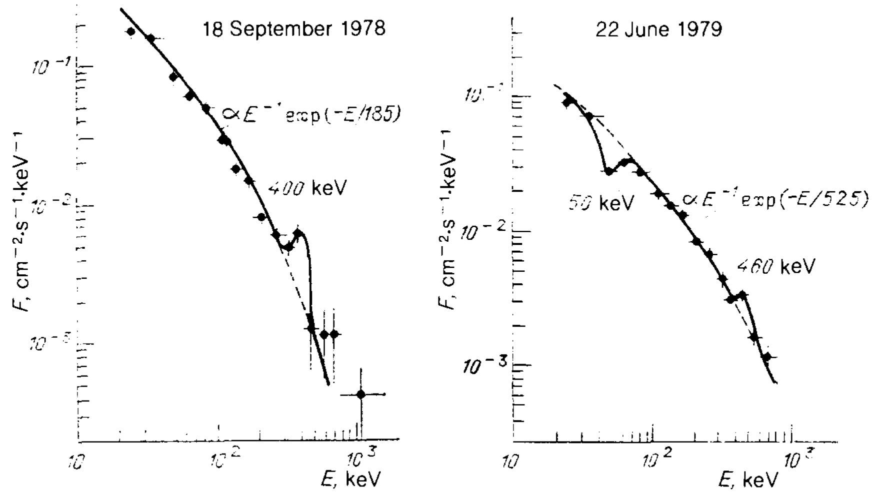

FIG. 3. Spectral features in the energy spectra of gamma bursts GB 780918 and GB 790622, according to data from the Konus experiment.[147]

ber of gamma bursts, in the course of different experiments[21b] (admittedly, there is some doubt regarding the feature at $E_\gamma \sim 400$ keV in the case of the SMM group[27]). The existence of these features can thus apparently be regarded as an established fact. Nevertheless, the interpretation outlined above cannot be judged definitive.

Yet another piece of evidence that neutron stars may be sources of gamma bursts was recently reported by Mirakami *et al.*[151] They found features in the spectra of bursts at 20 and 40 keV which they interpreted as the first and second harmonics of a cyclotron line. In principle, this interpretation indicates a strong magnetic field.

At the moment we also have something less than a clear picture of the specific physical mechanism which is responsible for the huge energy release. For example, the magnetic-field "annihilation" which appears to be the energy source of solar flares cannot explain the energy release which we would require under the conditions prevailing at a neutron star. As a result, either gravitational or nuclear energy is usually considered as a possible source of energy of the gamma bursts.[28]

The energy released when an asteroid or comet strikes the surface of a neutron star may be regarded as a pulsed release of gravitational energy. In this case the energy of the incident matter would reach a value of 100 MeV/nucleon, since at the surface of a neutron star we would have $|\varphi|/Mc^2 \sim 0.1$, where φ is the gravitational potential at the surface of the star.

Nuclear energy can be released in cases in which a neutron star is part of a binary system. During a prolonged accretion, a substantial amount of matter which has flowed out of the companion star may accumulate at the surface of the neutron star. A nuclear explosion of this matter leads to, in particular, the generation of gamma radiation.

Another possibility is that as a result of a starquake matter rich in heavy elements "pours out" of the interior of a neutron star onto the surface of the star. The subsequent decay of these elements leads to gamma radiation.

Each of these processes is capable of an energy release of the order of 10^{37}–10^{40} erg; i.e., they could be effective only if the gamma bursts were generated at distances $r \lesssim 1$ kpc.

In the opposite case (with $r \sim 100$ kpc and $W \sim 10^{44}$ erg), we need to seek other possibilities. Possibilities being considered are processes which occur within a star and lead to changes in its mass and rotation period and to surface vibrations. An upper limit of 10^{53} erg has been estimated for the energy which would be released in such processes. Consequently, even relatively small transformations involving a star would be capable of an energy release $W \approx 10^{44}$ erg. We might note in this connection that there are indications (albeit with a low statistical significance) that the envelope of the supernova from which the burst on 5 March 1979 was observed contains a pulsar with a period $\tau \approx 8.00 \pm 0.05$ s (Ref. 29; see also Ref. 152). Studies of this part of the sky which had been carried out on the Kosmos 856 vehicle slightly earlier, in 1977, also revealed pulsations (again, with poor statistics), but with a slightly shorter period, $\tau = 8.6 \pm 0.6$ (Ref. 30). If this effect—this decrease in period—is real, then by linking it with a change in the rotation of a neutron star we find a lower estimate of the amount of energy released: $\Delta W \approx 3 \cdot 10^{43}$ erg (Ref. 31).

The spectra of gamma bursts sometimes have features which can be identified with nuclear gamma lines.[23b,28] In particular, there is an indication that some gamma bursts have a feature at $E_\gamma \approx 740$ keV, which is interpreted as a shifted line of iron ($E_\gamma \approx 847$ keV).

3.2. $e^+ + e^- \rightarrow \gamma + \gamma$ annihilation line from the center of the galaxy

It was discovered in 1970 that the 0.511-MeV annihilation line (with a width less than 3.2 keV) was being emitted from near the galactic center.[32] It was not until later, in 1977, however, that this line was reliably identified.[33] It turns out that the radiation source lies near the galactic center (the uncertainty in the determination of the coordinates is $\pm 4°$). If we take the distance to the source to be 10 kpc, we can estimate the luminosity emitted in the line, L_γ. Using the flux observed at the earth, $F_\gamma \approx 10^{-3}$ photon/(cm^2·s), and assuming isotropic radiation, we find $L_\gamma \approx 3 \cdot 10^{37}$ erg/s. It follows that 10^{43} positrons per second are formed in the source[7a,c] if the emission is in a steady state.

Data obtained on HEAO-3 have proved important for reaching an understanding of the nature of this source.[34] It was found that the intensity of the radiation decreased by a factor of three in only 6 months (from late 1979 to early 1980). This intensity decrease was confirmed by later observations.[35] We thus find a limit on the dimensions of the source: 10^{18} cm according to the temporal variations (the size estimate follows from the simple relation $L \lesssim c\Delta t$, where Δt is the time scale of the variations in the radiation of the source, and c is the velocity of light). It also follows from the linewidth and time scale of the intensity variations that the temperature of the medium in the emission region must not have exceeded $5\cdot 10^4$ K, and the gas density must have exceeded 10^5 cm^{-3}, if the positrons were to be able to slow down sufficiently rapidly (in half a year).[36]

As possible sources we can thus rule out any families of stars (supernovae, pulsars, etc.) which are distributed near the center of the galaxy, since in such cases we would have to assume a high density of these stars in a region with a length scale of 10^{18} cm.

A more natural assumption is that there is some sort of peculiar source there.[7a,c,37] In particular, a black hole is being discussed as such a source in the literature. Model-based assumptions have yielded a limitation on the mass of the black hole: it must not exceed $10^6\, M_\odot$ (Ref. 38). However, there is the possibility that this mass is less than $10^2\, M_\odot$ (Ref. 39). These limitations are in no way related to the annihilation radiation which we discussed above.

Analysis of the data of Ref. 40 reveals yet another component of the e^+e^--annihilation radiation in the direction of the central region of the galaxy. These observations were carried out with the help of detectors having a fairly low angular resolution ($\gtrsim 50°$). The measured radiation flux turned out to be substantially higher than that provided by the source at the galactic center which we have been discussing. It was thus natural to suggest that this excess radiation was of a diffuse nature, i.e., was due to e^+e^- annihilation in interstellar space, where positrons are formed in the course of the nucleosynthesis of radioactive nuclei.

3.3. Line from ^{26}Al decay observed in the direction of the galactic center

A few years back, intense radiation in the line $E_\gamma = 1.8$MeV (with a linewidth no greater than 3 keV) was observed on the HEAO-3 (Ref. 41) and SMM (Ref. 42) satellites. This radiation was identified with the β decay of ^{26}Al, which is produced in nucleosynthesis processes in stars. The measured intensity of the line turned out to be $(6.4 \pm 2.61)\cdot 10^{-4}$ photon/(cm$^2\cdot$s). It has been suggested that the radiation which was detected is of diffuse origin, by which we mean that it comes from spatially distributed sources. Admittedly, the measurements were carried out by gamma-ray telescopes with a poor angular resolution (40° and 130° for HEAO-3 and SMM, respectively).

The observed radiation intensity was used as a basis for estimating the mass of ^{26}Al in the central part of the local galaxy. It was found to be 3 $M_\odot$. From this result follows a requirement on the sources: They must generate ^{26}Al at a mass rate of $3\cdot 10^{-6}\, M_\odot$/yr on the average. It turns out that this amount could not be produced in explosions of supernovae if their frequency at the galactic center is the same as that on the average over the entire galaxy. However, estimates showed that the required amount could be generated in the explosions of novae and also by Wolf-Rayet stars or pulsating red giants (see, for example, Refs. 78 and 43).

The further research on the source of the radiation in the ^{26}Al line involved an experiment carried out on a balloon at the Max Planck Institute (West Germany).[44] These observations revealed a pronounced concentration of the radiation toward the center of the galaxy. The dimensions of the radiation source did not exceed 10° (this limit follows from the angular resolution of the telescope). Hence one can suggest either a pronounced concentration of supernovae toward the galactic center[44] or the presence of some peculiar compact object there.[45] In connection with the latter model there is interest in the suggestion that the ^{26}Al line and the e^+e^- annihilation line coming from a region near the galactic center are of a common nature[46]: As a result of the decay of radioactive ^{26}Al, gamma rays ($E_\gamma = 1.8$ MeV) and positrons are formed. The annihilation of the positrons results in the generation of gamma rays with $E_\gamma = 0.51$ MeV.

3.4. Gamma lines from the source SS 433

A narrow line at 1.497 MeV was detected [47] from the galactic source SS 433. In addition, two spectral features were detected at $E_\gamma \approx 1.2$ MeV (Ref. 47) and 6.695 MeV (Ref. 48). The source SS 433 is a compact object, and according to optical and radio observations there are gas jets in it moving at a high velocity.

An interpretation of these spectral features in the emission from SS 433 is that they constitute Doppler-shifted gamma lines. For example, the line at 1.497 MeV is linked with a blueshifted line of ^{24}Mg (1.369 MeV) (Ref. 47) or with a line at 1.380 MeV generated in the course of the nuclear reaction $^{14}N(p,\gamma)^{15}O$ (Ref. 49). The lines at $E_\gamma = 1.2$ MeV (Ref. 50) and $E_\gamma = 6.695$ MeV (Ref. 51) are interpreted in a corresponding way.

3.5. Gamma lines from supernovae

The supernova explosion of 23 February 1987 in the Large Magellanic Cloud (supernova SN1987A) provided a special stimulus to research on the emission from supernovae in the gamma-ray range. Various elements, including radioactive elements, are produced in nucleosynthesis processes in stars. Accordingly, in the early stage of the development of a supernova (in accordance with the decay half-lives of the elements; §2) we would expect emission in lines of iron, titanium, aluminum, etc., from the supernova (Ref. 7a, for example).

In the early stages of the evolution of a supernova we would expect emission in a line of ^{56}Fe ($E_\gamma = 0.857$ MeV), which is produced in the β decay of ^{56}Co. The emission in this line might become visible at the time at which the envelope became transparent to the corresponding gamma rays. Numerical calculations for SN1987A show that the maximum in the emission in this line should occur about half a year after the explosion and that at this maximum the emission intensity should reach $2\cdot 10^{-4}$ photon/(cm$^2\cdot$s) (Ref. 52).

The observations which have been carried out to date (mid-1988) have provided the following results. Measurements at the Rentgen observatory at the Mir-Kvant complex and also on the Japanese satellite Ginga detected hard x radiation in the direction of SN1987A. According to one interpretation,[53] this radiation occurs during the "cooling" (Comptonization) of gamma rays with $E_\gamma = 0.857$ MeV as a result of their collisions with electrons in the optically thick envelope of a supernova.

As the envelope expands, and its transmission for gamma rays increases, the radiation should shift into the hard region until the line $E_\gamma = 0.857$ MeV becomes observable. In late 1987 there were reports of the detection of radiation from SN1987A in the lines $E_\gamma = 0.857$ MeV and $E_\gamma = 1.238$ MeV, which are generated in the decay of ^{56}Co (Ref. 54). The fluxes in these lines are 10^{-3} photon/($cm^2 \cdot s$) in order of magnitude. Interestingly, this radiation was detected six months earlier than predicted in the theoretical models. A possible reason for this result is discussed in Ref. 54c.

In later stages of the evolution of supernovae, a line from the decay of ^{44}Ti ($E_\gamma = 1.157$ MeV) may become observable. Since the decay half-life of ^{44}Ti is of the order of 100 yr—comparable to the time between supernova explosions in the local galaxy—this line is extremely promising for a search for supernovae which are invisible at other wavelengths.[55] Taking the average distance to the supernovae in the local galaxy to be 7 kpc, we would expect the flux in the line to be of the order of 10^{-5} photon/($cm^2 \cdot s$) (Ref. 56).

Research on the emission from relatively old supernova remnants reveals features which might be interpreted as gamma lines. For example, in the spectrum of the Crab Nebula one finds a feature at $E_\gamma = 80$ keV (Ref. 57). It seems possible that this feature is a cyclotron emission line which is generated in the magnetosphere of a pulsar, as is indicated by the subsequently discovered intensity variability of this "feature" at $E_\gamma \approx 80$ keV, with a period of 33 ms (Ref. 58).

A similar feature at $E_\gamma \approx 50$ keV was found in the spectrum of the source Her X-1 (Ref. 59a). It turns out that the radiation in this line is also variable. This result is strong evidence that the radiation is generated near a pulsar and is therefore of a cyclotron nature.

The cyclotron line at $E_\gamma \approx 10$–20 keV has also been observed from the source 4U 0115 + 63; correspondingly, we can estimate the magnetic field to be $H \approx 1.2 \cdot 10^{12}$ Oe (Ref. 59b).

4. DIFFUSE GAMMA RADIATION

The preceding section was devoted to an analysis of data at energies $E_\gamma < 30$ MeV. We turn now to energies $E_\gamma = 30$ MeV to 5 GeV. We are singling out this energy interval because it was studied in some detail on the satellites SAS-2 and COS-B.

We will then discuss the nature of the diffuse galactic gamma radiation, which is generated primarily by cosmic rays in interstellar space, as we will see. We will also present some characteristics of several discrete gamma sources.

4.1. Gamma radiation of the galactic disk; problem of the origin of the cosmic rays

Figure 4 shows the intensity distribution of the diffuse gamma radiation in three energy intervals: 70–150 MeV, 150–300 MeV, and 300 MeV–5 GeV. These results were obtained on the satellite COS-B (Ref. 60). A first look at this figure reveals that the preponderance of the observed flux comes from the region of the galactic disk. The diffuse gamma radiation is thus primarily of galactic origin. This origin distinguishes it in a substantial way from the "classical" x radiation (2–10 keV) whose diffuse component is isotropic, i.e., of metagalactic origin.[7h] The galaxy, on the other hand, constitutes a set of discrete sources in the x-ray range; only in certain parts of it can we see some small regions which are sources of diffuse radiation.

This aspect of the gamma radiation is particularly important for the problem of the origin of the cosmic rays. As we have already mentioned, the gamma radiation from the galactic disk is determined primarily by the interaction of cosmic rays with the interstellar gas. As can be seen from §2 of this review, the gamma radiation from the disk at energies $E_\gamma < 300$ MeV stems from the bremsstrahlung loss of relativistic electrons, while at $E_\gamma > 300$ MeV it stems from the decay of π^0 mesons which are produced in collisions of cosmic-ray protons and other nuclei with the interstellar gas. Gamma-ray astronomy thus presents a unique opportunity for studying the cosmic-ray distribution in the local galaxy and for determining the radiation intensity in various directions. Another factor making gamma-ray astronomy important for these purposes is that—in contrast with the electromagnetic radiation in other ranges (the radio, optical, and x-ray ranges)—the local galaxy is absolutely transparent in

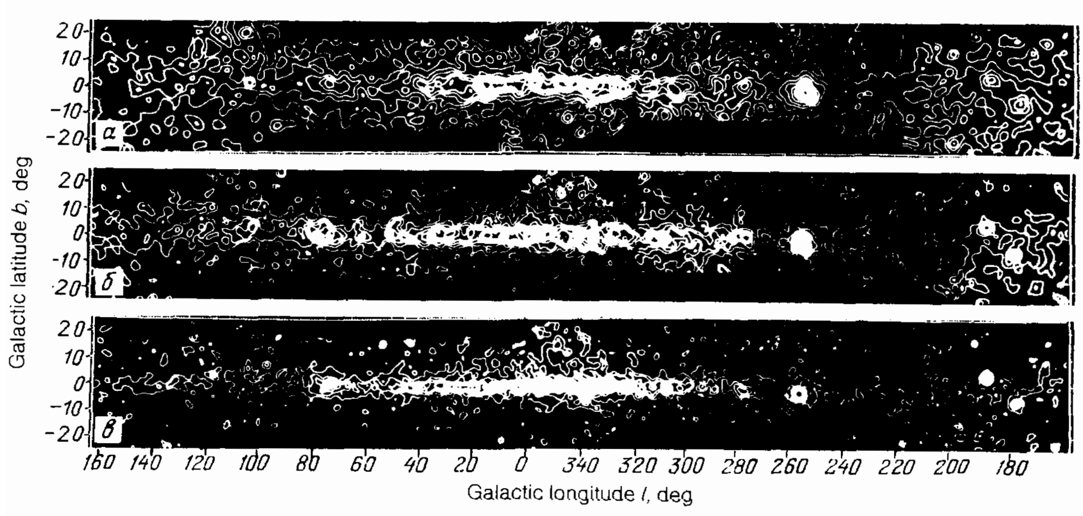

FIG. 4. Map of the diffuse gamma radiation. a—70–150 MeV; b—150–300 MeV; c—300 MeV to 5 Gev. The angular resolution of the COS-B telescope improves with increasing energy, as can be seen easily by comparing maps a and c.

the gamma-ray range: The range of gamma rays of these energies in the local galaxy is far greater than the size of this galaxy (Table IV).

The problem of the origin of cosmic rays has a fairly long history (Ref. 61, for example). One aspect of this problem which is still being discussed is that of identifying the positions of the sources of the particles whose flux we observe as cosmic rays at the earth. The debate on this question has heated up again specifically because of observational results in the gamma-ray range.[62]

One camp adheres to metagalactic models of the origin of the cosmic rays. The primary sources of the cosmic rays are outside the local galaxy. These sources might be the most powerful galaxies in the galactic supercluster closest to us, e.g., the radio galaxy NGC 4151 (models in which the sources are even more remote run into even greater difficulties). In this case the length scales of the variation in the *cosmic-ray density are substantially greater than the dimensions of galaxies and even the distance between closest galaxies*. In such models, the densities and spectrum of the bulk of the cosmic rays should be approximately the same throughout the local galaxy and in the galaxies closest to us, the Large and Small Magellanic Clouds. Metagalactic models have been criticized repeatedly for a long time now (see, for example, Refs. 10f and 61), and today they look very improbable (we are not talking about cosmic rays with ultrahigh energies $E_\gamma \gtrsim 10^{17}$–10^{19} eV).

In contrast, galactic models appear quite acceptable (although, strictly speaking, they have not been definitively proved). In application to the local galaxy, the primary sources of particles in such models of the origin of the cosmic rays lie inside the local galaxy itself. These sources might be supernovae, pulsars, and perhaps active stars of some sort (O stars, etc.). Most of the stars in the galaxy are in the galactic disk. The radius of the stellar and gaseous disk is about 15–20 kpc, and its thickness varies over the range 100–400 pc for various types of stars (Fig. 5). The stars which we just mentioned (supernovae and pulsars) are concentrated closer to the central part of the galactic disk (Fig. 6). One is led to ask just how the cosmic rays emitted by the sources are distributed in the galaxy as a whole and in the galactic disk in particular. The answer to this question depends on

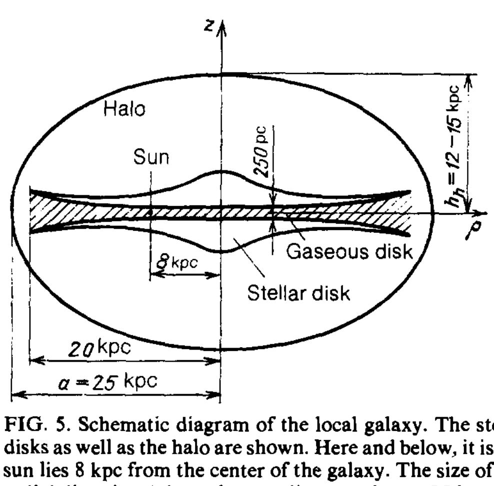

FIG. 5. Schematic diagram of the local galaxy. The stellar and gaseous disks as well as the halo are shown. Here and below, it is assumed that the sun lies 8 kpc from the center of the galaxy. The size of the galaxy in the radial direction (along the coordinate ρ) is $a = 25$ kpc, while that in the direction perpendicular to the galactic plane (along the coordinate z) is $h_h = 12$–15 kpc.

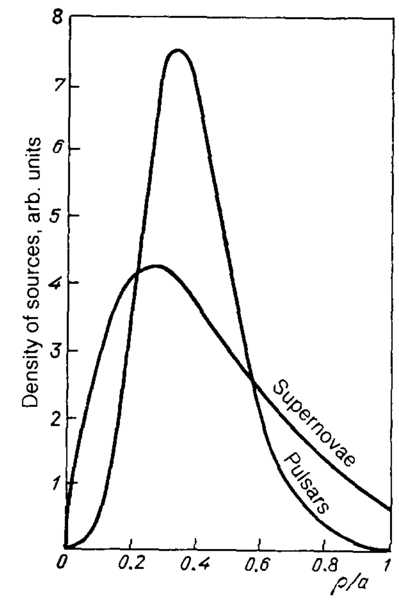

FIG. 6. Distribution of the density of probable sources (supernovae and pulsars) of cosmic rays in the galactic disk along the radius ρ (here $a = 25$ kpc).

1) how the cosmic rays propagate through the galaxy,

2) the dimensions of the region in which the cosmic rays are "confined," and

3) the conditions at the boundary of this confinement region. (Do the particles escape freely into metagalactic space, or are they reflected back from these boundaries in accordance with the "closed-box model?")[61a,63]

All these questions are discussed in some detail in monographs,[8b,61a,64] so we will simply summarize three basic positions.

1. The nature of the propagation of cosmic rays in the local galaxy is determined by their interaction with the interstellar magnetic fields. Collisions of a particle with inhomogeneities of the magnetic field $H(r)$ occur at a rate

$$\nu_\mu \approx 2\pi^2 \,|\omega_H|\, \frac{k_{\rm res} W^{\pm}(k_{\rm res})}{H_0^2}. \tag{4.1}$$

Here $\omega_H - eH_0/mc$ is the Larmor frequency of a nonrelativistic particle;

$$k_{\rm res} = \frac{1}{r_H} = \frac{eH\mu}{mc^2}\,\frac{mc^2}{E},$$

where r_H is the Larmor radius of the particle; $W(k)$ is the Fourier transform of the energy density of the magnetic inhomogeneities of scale $r \sim 1/k$, given by

$$W(k) = \frac{1}{(2\pi)^3} \int \frac{\mathbf{H}^2(\mathbf{r})}{8\pi}\, e^{i\mathbf{kr}}\, d\mathbf{r},$$

where $H_0^2/8\pi$ is the energy density of the large-scale galactic magnetic field (here $H < H_0$); and the $\pm$ specify collisions with inhomogeneities which are moving in the two directions along a magnetic field line. The motion of a particle along H_0 can usually be described as a diffusion with a coefficient

$$D_\parallel = \frac{v^2}{2} \int_0^1 \frac{1-\mu^2}{\nu_\mu^+ + \nu_\mu^-}\, d\mu, \tag{4.2}$$

where v is the velocity of the particle, and μ is the cosine of its pitch angle (i.e., of the angle between $\mathbf{v}$ and $\mathbf{H}_0$). A crude estimate of expression (4.2) is

$$D_{\parallel} \sim v^2\tau, \tag{4.3}$$

where τ is determined by the value of the integral in (4.2). It is the time over which the pitch angle of the particle changes by about $\pi/2$.

Since the magnetic field lines are "tangled," the motion of a particle across the average direction of the field $\mathbf{H}_0$ can also be described as a diffusion $D_{\perp}$ (Refs. 8b and 65). Since the quantities $D_{\parallel}$ and $D_{\perp}$ are roughly equal, the overall motion of a charged particle in the galactic magnetic fields is described in a first approximation as *isotropic* diffusion.[8b]

Furthermore, if the collision rates in the + and − directions are different, the particle begins to move at an average velocity u (Refs. 8b and 66) given by

$$u = V_A \int_0^1 \frac{3(1-\mu^2)}{2} \frac{\nu_\mu^+ - \nu_\mu^-}{\nu_\mu^+ + \nu_\mu^-} d\mu. \tag{4.4}$$

The motion of cosmic rays in the galaxy can thus be described by the equation (we are assuming a steady-state picture)

$$-\nabla (D\nabla f - \mathbf{u}f) + \hat{L}(E) f = Q(\mathbf{r}, E); \tag{4.5}$$

here $f(\mathbf{r},E)$ is the distribution function of the particles, $\hat{L}(E)$ is the energy loss of the particles or the disappearance of these particles in interstellar space, and $Q(\mathbf{r},E)$ is the spatial distribution of the sources of cosmic rays which inject particles with an energy E. Skipping over the details, we note that an analysis of the set of observational data (see Chaps. 3 and 4 in Ref. 8b) reveals that a diffusive transport of cosmic rays is predominant in the local galaxy. If convection plays any role in the propagation processes, it is probably a secondary one.

2. It has been clear for a long time now on the basis of general considerations[67] that the region in which the cosmic rays propagate cannot be confined to the stellar disk and is instead a quasisphere with a radius of the order of 10 kpc surrounding the disk (Fig. 5). This region is the "cosmic-ray halo" of the galaxy.[4)] Cosmic rays may be retained in the halo for a long time before they escape into intergalactic space. This statement means that both the density of cosmic rays and (probably) the magnetic field strength in the halo have values only insignificantly different from those in the disk. For a long time it was not found possible to construct any strong argument in favor of the existence of a galactic halo. Today, on the other hand, we have completely definite indications that the galaxy does have a cosmic-ray halo. We turn now to a discussion of these indications.

a) The electron component of the cosmic rays creates a radio halo; here we are talking about the synchrotron radio emission by relativistic electrons which are moving in the magnetic field of the halo, i.e., in the magnetic halo.

In principle, the size of the radio halo can be found from an analysis of the intensity of the diffuse galactic radio emission in the direction perpendicular to the galactic disk. The intensity of the radio emission can be described crudely by [see (2.28)]

$$I_\nu \propto LHJ_e, \tag{4.6}$$

where J_e is the average intensity of the electrons, and H is the magnetic field strength. Making use of the observed intensity of the radio emission in the various directions, we can estimate the size of the region filled by cosmic-ray electrons and magnetic field. Analysis of the diffuse radio emission[8b,69] has shown that the typical size of the radio halo of the galaxy is of the order of 5–10 kpc. Furthermore, the diffusion coefficient D was found as a function of the size (half-thickness) of the radio halo, h_h, on the basis of radio data in Ref. 69a. A similar $D(h_h)$ dependence was found from an analysis of data on the chemical composition of the cosmic rays.[70] These two results are plotted in Fig. 7 as curves of $D(h_h)$, which we see intersect at a single point: $h_h \approx 12$ kpc, $D \approx 10^{29}$ cm^2/s. Consequently, only in a model with a large halo ($h_h \approx 12$ kpc) and with an effective mixing of the cosmic rays ($D \sim 10^{29}$ cm^2/s) would it be possible to obtain the set of cosmic-ray characteristics which correspond to the observed values. Admittedly, all these observational data as well as the calculations need further refinement.

b) Analysis of the Faraday rotation of the polarization plane of the galactic and extragalactic radio sources and measurements of the degree of polarization of the radio emission of galaxies seen edge-on suggest that the local galaxy and also other galaxies have a halo of "magnetic fields" (a magnetic halo) which surrounds the galactic disk and is of a scale no smaller than 3 kpc, with a relatively strong magnetic field.[71]

c) Observations of certain galaxies in the radio range reveal vast radio halos, with sizes of a few kiloparsecs.[72]

3. In this formulation of the problem, we also need to examine the question of whether the particles flow freely out into intergalactic space or are reflected back from the boundaries of the halo. In the former case, the electron spectrum should be found to have a slope change at energies corresponding to the equality of the duration of the energy loss and the duration of the diffusive outflow from the local galaxy.[10g] At the presumed parameter values of the cosmic-ray halo ($h_h \approx 12$ kpc), this slope change in the electron spectrum should occur at an electron energy of the order of hundreds of megaelectron volts. In a model with reflection, there would be no such slope change.

The spectrum of cosmic-ray electrons in this energy region cannot be determined directly at the earth because of a modulation in the vicinity of the sun. It can, on the other

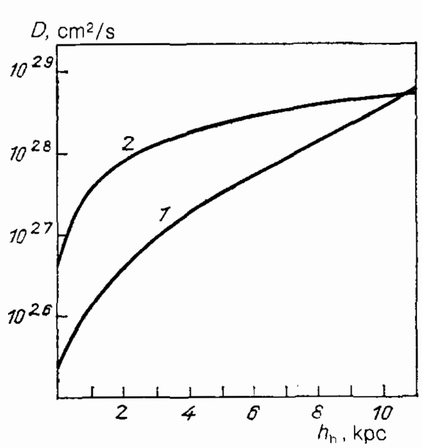

FIG. 7. The diffusion coefficient D as a function of the size of the halo, h_h. 1—Calculated from an analysis of data on the chemical composition of cosmic rays; 2—found from data on the electron component of cosmic rays and the diffuse galactic radio background.

hand, be reconstructed from an analysis of the diffuse radio and low-energy gamma radiation, which is determined by the synchrotron and bremsstrahlung losses of these electrons [see expressions (4.8a) below].[73,74] According to the results of these studies, there apparently is indeed a slope change in the electron spectrum at the energy given above; in principle, this slope change may be evidence of a free escape of cosmic rays.

We have thus refined the characteristics of the model (characteristics 1, 2, and 3) within which we will analyze the problem of the origin of cosmic rays: a diffusion model with a halo and with a free escape of particles.

Before we turn to the direct analysis of certain gamma-ray-astronomy data, we not that we have always adhered to specifically a galactic model for the origin of the bulk of the cosmic rays (although we acknowledge that in the past that opinion was based on only indirect data). Specifically, we might point out the following:

1) The electron component of the cosmic rays is clearly of galactic origin. Because of the Compton loss in collisions with photons of the background radiation in intergalactic space, electrons could not reach us even from the nearest radio galaxy, NGC 4151 (Refs. 10f and 8b).

2) There are undoubtedly sources in the local galaxy which could provide the entire cosmic-ray luminosity which would be required ($L_{cr} \sim 10^{40}$–10^{41} erg/s). Supernova explosions would qualify here.[61] Curve 1 in Fig. 6 shows the distribution of supernovae in the galactic disk.

Using this galactic model, we can calculate the expected distribution of the density of cosmic rays. The results of such a calculation are shown by curve 1 in Fig. 8. As the sources of cosmic rays in calculations we adopted supernovae, whose distribution in the galactic disk is shown by curve 1 in Fig. 6.

The fairly large value of the diffusion coefficient in the local galaxy and the presence of a vast halo around this galaxy are seen to lead to an effective mixing of cosmic rays. As a result, the distribution of cosmic rays in the disk (curve 1 in Fig. 8) is quite different from the distribution of sources (curve 1 in Fig. 6).

Nevertheless, this model has the characteristic feature that the cosmic-ray density should fall off toward the periphery of the disk, as we see. We thus recognize a criterion for deciding whether cosmic rays are galactic or metagalactic in origin: In the former case we would observe a gradient of the cosmic rays, and in the latter case we would not.

This question might be decided by analyzing the diffuse gamma radiation from the galactic disk. Specifically, as we have already mentioned, the gamma radiation of the disk at energies $E_\gamma > 300$ MeV is determined by the interaction of the proton-nucleus component, which constitutes the preponderance of the cosmic rays, with the interstellar gas.

To evaluate the intensity of the gamma radiation, we use an approximate expression of the type [see (2.31)]

$$J_\gamma \sim n_g J_{cr} L, \tag{4.7}$$

where n_g is the average gas density, J_{cr} is the intensity of protons, and L is the size of the part of the disk which is filled with gas and cosmic rays. It can be seen from a comparison of expressions (4.6) and (4.7) that gamma-ray astronomy is as important for studying the proton-nucleus component as radio astronomy is for the electron component. As in the case of the analysis of the electron distribution in the galaxy on the basis of radio data, which we discussed above, gamma-ray astronomy makes it possible to estimate the density of cosmic-ray protons in various parts of the galactic disk.

Admittedly, we need to know the gas distribution in the galaxy in order to do this. We know that most of the gas in the galactic disk is in two components: atomic and molecular hydrogen (Fig. 9). The distribution of the first of these components is known fairly well from radio data (the 21-cm line). The total mass of atomic hydrogen is equal to about $5 \cdot 10^9 M_\odot$; about 20% of this mass is in the inner part of the galactic disk, i.e., in a region whose center coincides with that of the galaxy and which has a radius of 8 kpc, where 8 kpc is the distance from the center of the disk to the sun. The other 80% of the atomic hydrogen is in the outer part of the disk, i.e., the part of the disk whose radius exceeds 8 kpc. In the central part, the thickness of the atomic-hydrogen disk is 200 pc; toward the periphery it increases to 1000 pc (Fig. 5).

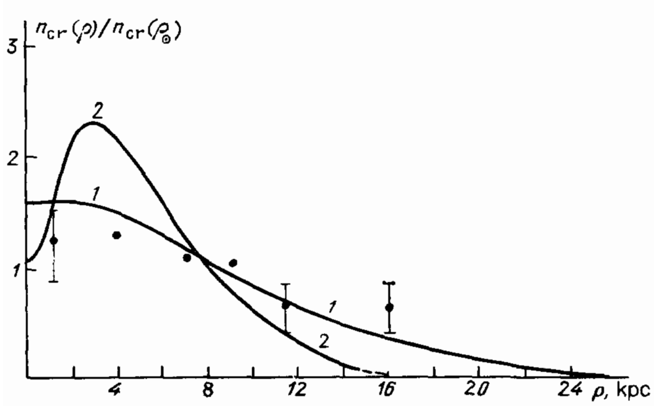

FIG. 8. Distribution of the relative cosmic-ray density in the galactic disk along the disk radius ρ. Here $n_{cr}(\rho_\odot)$ is the cosmic-ray density near the earth, and $\rho_\odot \approx 8$ kpc. 1) Distribution of cosmic rays in the disk if the local galaxy has a vast halo, with $h_h \approx 15$ kpc; 2) distribution of cosmic rays in the disk if the size of the halo is $h_h = 600$ pc.

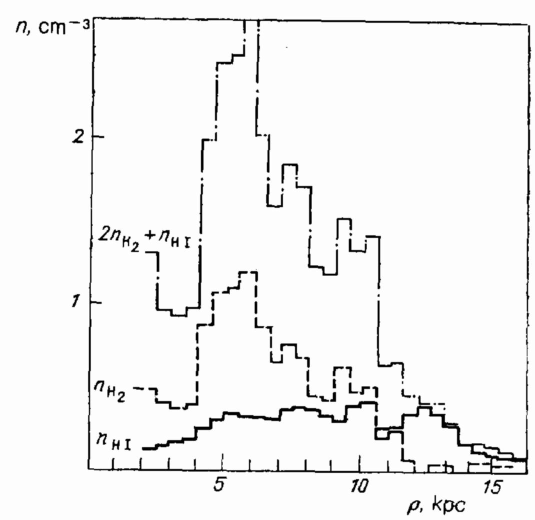

FIG. 9. Distribution of the densities of atomic hydrogen (HI) and molecular hydrogen (H_2) in the galactic disk.

Most of the molecular hydrogen is in the inner part of the galactic disk. Its mass is estimated from a CO line (2.6 mm), whose excitation is linked with collisions of H_2 and CO molecules. The procedure by which the mass of H_2 is estimated involves several assumptions, so the values which have been found from the data of different investigators span a fairly wide range. On the whole, we can apparently assume that the mass of H_2 in the inner part of the galaxy is $10^9\ M_\odot$ and that it constitutes up to 50% of the total mass of gas there.[75]

Several attempts have been made to estimate the cosmic-ray gradient from gamma-ray data.[62] The most recent results based on the COS-B data, from Ref. 7e, are shown in Fig. 8. In our opinion, these data do not, within the errors, contradict calculations of the cosmic-ray gradient found on the basis of the model which we are discussing here. Incidentally, they are apparently also consistent with a uniform distribution of cosmic rays.

An important conclusion which follows from an analysis of the gamma-ray data is that the gradient of the cosmic rays, if it exists (and it seems to us that its existence will undoubtedly be confirmed in future experiments), is small. It is thus clear that the experimental data point to an effective mixing of cosmic rays in the galaxy. This mixing would be possible only in a diffusion model. Furthermore, the calculated distributions of the cosmic-ray density, n_{cr}, in the disk can be associated with the n_{cr} distribution found from the gamma-ray data[7e] only if the size of the galaxy in the radial direction is quite large, $a \approx 25$ kpc, and the halo is also large, $h_h \approx 15$ kpc (Fig. 5). The gamma-ray data thus indicate a large halo and a diffusive propagation of the cosmic rays.

As an example, Fig. 8 shows the results of a calculation of the cosmic-ray density in a model with a small halo ($h_h = 600$ pc); this small halo serves as an obstacle to the mixing of cosmic rays in this case (the results of the calculation are shown by curve 2 in Fig. 8).

We see that in this case the cosmic-ray distribution becomes similar to the distribution of the sources of the cosmic rays (compare curve 1 in Fig. 6 with curve 2 in Fig. 8).

We can also point out two important aspects of the diffuse gamma radiation from the galactic disk:

1. Most of the radiation from the galactic disk is associated with interactions of cosmic rays with gas. This conclusion follows in particular from the good correlation, according to Ref. 75, between the intensity of the gamma radiation and the thickness of the gas in various directions.

2. A substantial part ($\sim 50\%$) of the gamma radiation from the galactic disk, whose luminosity at $E_\gamma \gtrsim 100$ MeV is of the order of 10^{39} erg/s, is formed in the inner part of the disk, i.e., at $\rho > 8$ kpc (Ref. 76). Furthermore, a significant gamma-ray flux is observed even in parts of the galactic disk which are quite remote from the center, out to $\rho \sim 16$–18 kpc (Ref. 76). It follows that even in these peripheral regions the gas density and the cosmic-ray density are still high.

4.2. High-latitude gamma radiation; gamma-ray halo of the galaxy

The question of the origin of the high-altitude radiation (somewhat arbitrarily, the radiation for galactic latitudes $b \gtrsim 10°$) is less clear than that for the low-latitude radiation ($b < 10°$), which is determined primarily by the radiation of the galactic disk. Since the problem of the high-latitude gamma radiation has essentially escaped discussion in the literature, and it is basically a new problem, we will take a fairly detailed look at it.

The following are being considered as possible sources of the high-latitude radiation:

a) the interaction of cosmic rays with the gas in the local neighborhood of the galactic disk (i.e., at distances less than a few hundred parsecs from the earth);

b) the interaction of cosmic rays with photons and gas in the halo;

c) the radiation of the metagalaxy.

In this list of possible sources of the high-latitude radiation, the item which attracts greatest interest is the role of the halo, since the existence of radiation from the disk and the metagalaxy is beyond dispute. The existence of a significant gamma-ray halo, on the other hand, is not as obvious.

A gamma-ray halo should be linked primarily with the Compton loss of relativistic electrons, since the gas density in the halo is probably too low for any significant corresponding gamma radiation.[77] The galactic halo is filled with photons of various energies. These are photons of the background radiation, which has an average energy $\varepsilon_{ph} \approx 6.7 \cdot 10^{-4}$ eV and which uniformly fill the entire space with an energy density $w_{ph} \approx 0.25$ eV/cm^3 ($\varepsilon_{ph} \approx 2.43 \cdot 10^{-4} T$; $T = 2.7$ K). Furthermore, the halo contains IR photons ($\varepsilon_{ph} \sim 0.1$–$10^{-2}$ eV) and optical photons ($\varepsilon_{ph} \sim 1$ eV) of galactic origin (neutron stars, dust clouds, etc.). These photons are distributed in a spatially nonuniform way.[78] At the maximum (in the central region of the galaxy), the energy density w_{ph} can reach a few electron volts per cubic centimeter, but it falls off rapidly with distance from the galactic center.

We can estimate the average energy of a relativistic electron which, being scattered by these photons, generates gamma rays with an average energy $E_\gamma = 100$ MeV. Using expression (2.23), we find Table V.

Because of the uncertainty regarding the distribution of IR and optical photons, which we mentioned above, the scattering of electrons by these photons would appear to be important only in the central region of the galaxy. The gamma radiation of the peripheral regions of the galaxy is due primarily to scattering by photons of the background radiation.[79]

In contrast with the radiation from the galactic disk, where gamma rays with $E_\gamma \approx 100$ MeV are generated by low-energy electrons ($E_e \approx 300$ MeV), in the halo this radiation is thus due to high-energy electrons with $E_e \sim 100$ GeV.

Because of the energy losses (synchrotron and Compton),

TABLE V.

Type of photon	Electron energy $E_e = mc^2(3E_\gamma/4\varepsilon_{ph})^{1/2}$, GeV
Optical ($\varepsilon_{ph} \approx 1$eV)	4
IR ($\varepsilon_{ph} \approx 10^{-2}$ eV)	40
Background ($\varepsilon_{ph} \approx 6.7 \cdot 10^{-4}$ eV)	150

$$\frac{dE}{dt} \equiv bE = -\beta E^2,$$
$$\beta = \frac{32\pi c}{9}\left(\frac{e^2}{mc^2}\right)^2\left(w_{\text{ph}} + \frac{H^2}{8\pi}\right)\left(\frac{1}{mc^2}\right)^2, \tag{4.8a}$$

electrons of such high energies could not fill the entire volume of the halo. The lifetime of such electrons in the galaxy is determined by

$$\tau(E) = \int \frac{dE}{b(E)},$$

and if the diffusion coefficient D is constant throughout interstellar space an electron can move a distance $\lambda(E) \sim (D\tau(E))^{1/2}$ on the average from the point at which it is produced. If the diffusion coefficient depends on the electron energy, $D = D(E)$, the range of the electrons, $\lambda(E)$, is given by[80]

$$\lambda^2(E) = \int \frac{D(E)}{b(E)}\, d(E). \tag{4.8b}$$

The typical size of the halo region filled with high-energy electrons produced in the galactic disk is thus determined by the value of $\lambda(E) < h_{\text{h}}$.

For a galactic diffusion coefficient of the form [10g]

$$D(E) = D_0\left(\frac{E}{E_0}\right)^{\mu}, \quad E > E_0, \tag{4.9}$$

where $D_0 \sim 10^{29}$ cm^2/s, $E_0 \sim 1$ GeV and $\mu \approx 0.4$–0.6, the size of the region, $\lambda(E)$, has an energy dependence

$$\lambda(E) \propto E^{-(1-\mu)/2} = E^{-(0.2-0.3)}. \tag{4.10}$$

The results of numerical calculations of the distribution of electrons of various energies in the halo are shown in Fig. 10 (z is the coordinate running perpendicular to the galactic plane).

In previous calculations on the gamma radiation of the halo, the change in the electron energy in the halo itself was usually ignored; i.e., it was assumed that the distribution of electrons in the halo does not depend on the energy. In this case we can write

$$J_\gamma \propto J_e(E)\, h_{\text{h}}, \tag{4.11}$$

where h_{h} is a typical size of the halo. Actually, as is clear from (4.8) and the specific calculations, the typical size of the halo differs from one electron energy to another. The intensity of the gamma radiation of the halo is thus described by

$$J_\gamma \propto J_e(E)\, \lambda(E). \tag{4.12}$$

Using expression (2.24) and (4.12), we see that the dependence of the intensity of the gamma radiation of the halo, J_γ, on the gamma-ray energy E_γ, in the direction perpendicular to the galactic disk, is

$$J_\gamma \propto E_\gamma^{-(\gamma_0+2)/2} = E_\gamma^{-(2.1-2.15)}. \tag{4.13}$$

The spectral index of the halo is constant, about 2.1, over a fairly broad range of gamma-ray energies: from tens of kiloelectron volts to tens of gigaelectron volts. Here γ_0 is the spectral index of the electrons which are injected by galactic sources; it is found by comparing the electron spectra at the earth with radio data. The value of γ_0 is 2.1–2.4 (Ref. 8b, 62b, and 69a).

We will also point out some spectral characteristics of other components of the high-latitude radiation.

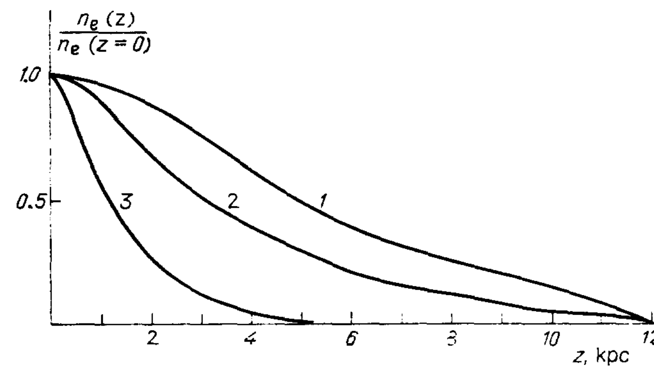

FIG. 8. Distribution of the relative cosmic-ray density in the galactic disk along the disk radius ρ. Here $n_{cr}(\rho\odot)$ is the cosmic-ray density near the earth, and $\rho\odot \approx 8$ kpc. 1) Distribution of cosmic rays in the disk if the local galaxy has a vast halo, with $h_{\text{h}} \approx 15$ kpc; 2) distribution of cosmic rays in the disk if the size of the halo is $h_{\text{h}} = 600$ pc.

The bremsstrahlung of electrons in the disk is important at gamma-ray energies $E_\gamma < 100$ MeV. This radiation is generated by electrons with $E < 300$ MeV, which have a spectrum $J_e \propto E^{-(2.1-2.3)}$ in this energy range according to radio data.[62b,69a,73] The spectrum of bremsstrahlung photons is then described by

$$J_\gamma(E_\gamma) \propto E_\gamma^{-(2.1-2.3)}. \tag{4.14}$$

At higher energies, $E_\gamma \gtrsim 300$ MeV, the gamma-ray spectrum is determined by the decay of π^0 mesons, while at gamma-ray energies above a few gigaelectron volts it reproduces the spectrum of cosmic-ray protons:

$$J_\gamma(E_\gamma) \propto E_\gamma^{-2.75}. \tag{4.15}$$

The soft gamma radiation, $E_\gamma \lesssim 10$ MeV, is probably of metagalactic origin and has a spectrum[81]

$$J_\gamma(E_\gamma) \propto E_\gamma^{-2.7}. \tag{4.16}$$

For convenience below, we will use the term (a) "gaseous" gamma radiation to mean the radiation from the galactic disk which is generated as a result of the interaction of cosmic rays with atomic and molecular hydrogen and the term (b) "photon" gamma radiation to represent the gamma radiation of the galactic halo, formed through the Compton scattering of relativistic electrons by low-energy photons. Consequently, the gamma-ray flux for any observation direction is equal to the sum of the gaseous, photon, and metagalactic components.

In contrast with the nonthermal radio emission, which is of a synchrotron nature in both the disk and the halo, the gamma radiation consists of several components, with distinct spectral characteristics. Consequently, some one component may be the governing component in the observed flux, depending on the energy interval or the particular direction studied; correspondingly, the characteristics of the radiation may change.

We would also like to stress the fact that the characteristics of the radio disk and the gamma-ray disk are not identical. While the radio-emitting electrons ($E \simeq 100$ MeV–10 GeV) fill a quasispherical region [for them, the relation $\lambda(E) \gtrsim h_h$ holds], the halo in the gamma-ray range ($E_\gamma \simeq 100$ MeV) is probably a thick disk, with a thickness of 1–3 kpc, rather than a sphere (Fig. 11). The reason is that the gamma rays in the halo are generated by electrons with an extremely large energy ($E \sim 100$ GeV; Fig. 10), for which the relation $\lambda(E) < h_h$ holds. It follows in particular that, while the intensity of the radiation from a quasispherical radio halo has comparable magnitudes in the directions along and perpendicular to the galactic plane, the radiating thickness of the gamma-ray halo is largest for low-latitude directions, with $b \lesssim 10°$ (the effect should be particularly obvious in the direction of the center of the galaxy; Fig. 11).

Finally, the entire range of nonthermal radio emission (from tens of megahertz to a few gigahertz) is determined by the radiation of electrons with energies lying in the comparatively narrow interval from hundreds of megaelectron volts to several gigaelectron volts. In the gamma-ray range, the emission of gamma rays even of the same energy (say $E_\gamma \simeq 100$ MeV) may be caused by either the bremsstrahlung of relatively low-energy electrons ($E \sim 100$ MeV) or the Compton scattering of high-energy electrons ($E \sim 100$ GeV).

The spatial distribution of the cosmic-ray density, which we need in order to estimate the intensities of the various components of the galactic gamma-ray radiation, has been calculated on the basis of the diffusion model for the propagation of cosmic rays which we discussed above. The results of numerical calculations[62b] of the intensity of the gamma radiation of the galaxy in the direction perpendicular to the galactic plane are shown in Fig. 12. We see from this figure that the galactic radiation can constitute a significant fraction of the observed high-latitude flux. An important point here is that the numerical calculations[62b] show that the halo radiation can be a substantial fraction of the total flux of the galaxy.

In this connection it is important to stress the following point: At one time it was believed rather widely that most of the galactic gamma radiation was due exclusively to radiation from the disk, which was generated in a local galactic neighborhood, for moderate and high latitudes, $|b| > 5°$ (Ref. 84, for example). However, calculations of the gamma-ray intensity[62b] have shown—somewhat unexpectedly—that the halo can represent a fairly large fraction of the observed flux: It can amount to some tenths of the observed high-latitude flux. Consequently, at high latitudes and (by virtue of the discussion above) especially at moderate latitudes (Fig. 11) we would expect observable gamma-ray effects associated with the halo.

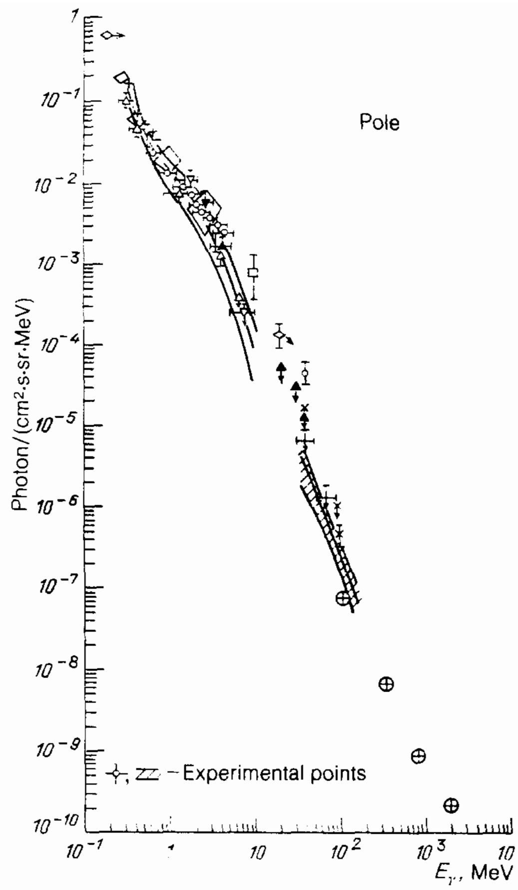

FIG. 12. Spectrum of the gamma radiation observed in the direction of the pole of the local galaxy (perpendicular to the galactic plane).[81a] Also shown here are results calculated on the high-latitude gamma radiation on the basis of the diffusion model of the galaxy, with a wide halo (⊕), which is under discussion here.[62]

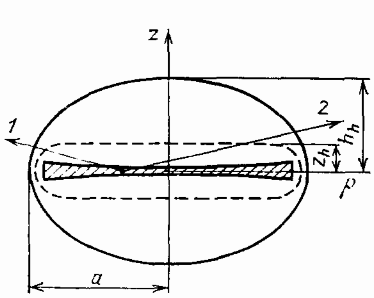

FIG. 11. Diagram of the local galaxy. Shown here are the gaseous disk (the hatched region), the cosmic-ray halo (of size h_h), and the gamma-ray halo for $E_\gamma = 100$ MeV, which is a consequence of the scattering of electrons by photons of the background radiation (the region shown by the dashed line, with a size z_h). Also shown here are the directions toward the anticenter (1) and the center (2), in which the halo radiation is the largest fraction of the total gamma-ray flux observed at the earth. ($a = 25$ kpc, $h_h = 12$ kpc).

Let us first see whether there are any observational indications of the existence of a gamma-ray halo.

The first detailed measurements of the flux of diffuse radiation were carried out on the satellite SAS-2. The high-latitude flux in the energy range 30–150 MeV was also measured (see Fig. 12; the hatching in the figure shows the SAS-2 measurements). Part of this radiation was linked with exclusively radiation from the disk, while the remainder was assumed to be isotropic metagalactic radiation (see, for example, the review by Gal'per[82]). In other words, the galactic gamma radiation was assumed to be of an exclusively "gaseous" nature. Subsequent measurements carried out on the COS-B were concerned primarily with low and moderate latitudes ($|b| \lesssim 30°$), although the flux in the high-latitude direction was also measured (albeit in a small part of the sky, and with a poor statistical base; Fig. 13).

Analysis of the gamma radiation in the low-latitude direction, $|b| < 5°$, revealed a good correlation between the

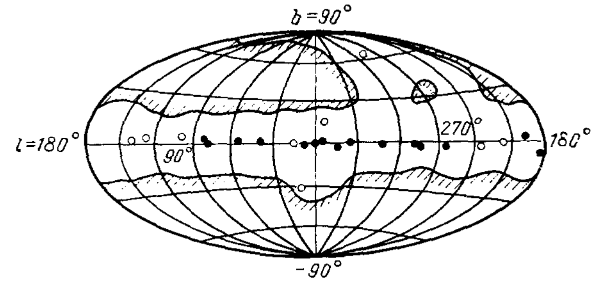

FIG. 13. Distribution of COS-B sources over the celestial sphere (in terms of the galactic coordinates l, b). Filled circles—Sources with a flux $> 1.3\cdot 10^{-6}$ photon/cm$^2\cdot$s); open circles, with fluxes below this limit (for energies $E_g > 100$ MeV). The part of the sky which was studied by COS-B is separated from the part which was not studied by hatching.

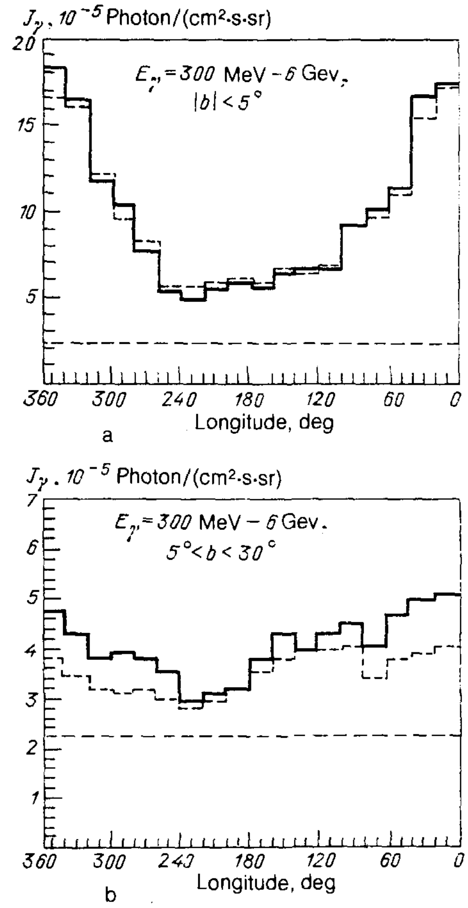

FIG. 14. Profile of the gamma-ray intensity in the range $E_g = 300$ MeV–6 GeV along the galactic longitude l. Solid line—observed radiation; dashed line—estimated contribution of radiation from the galactic disk, which is determined by the interaction of cosmic rays with gas.[86] a) For galactic latitudes $|b| < 5°$; b) for latitudes $5° < b < 30°$.

measured intensity of the gamma radiation and the total thickness of gas (atomic hydrogen plus molecular hydrogen). It was thus shown that the radiation from the galactic disk is generated primarily through an interaction of cosmic rays with the interstellar gas and that the role played by discrete gamma sources is probably a small one (Fig. 14a).

Carrying out a corresponding analysis in the direction of intermediate latitudes, $|b| \lesssim 30°$, is complicated by the absence of data on the distribution of molecular hydrogen. In several studies, however, the total gas thickness in these directions has been estimated on the basis of the variations in the number of galaxies along observation direction. It was assumed that these variations are a consequence of the absorption of optical radiation by interstellar dust and that the thickness of the dust is proportional to the total thickness of the gas.[83] It was asserted on this basis in Ref. 84 that there is a fairly good correlation between the intensity of the gamma radiation and the total gas thickness estimated in this way. It follows that the gamma radiation in the direction of intermediate latitudes is also due primarily to the interaction of cosmic rays with the interstellar gas for latitudes $|b| > 5°$. Since the thickness of the gas disk is hundreds of parsecs, the radiation observed at $|b| \gtrsim 10°$ is formed in a so-called local galactic neighborhood; i.e., it is generated at distances less than several hundred parsecs from the earth (Fig. 11). Under these assumptions, and knowing the gas thickness, we can estimate the emissivity in the gamma range, $q_1(E_\gamma)$ [see (2.29)], near the earth (Table VI). The integral local emissivity over the energy range from 70 MeV to 5 GeV is[84] $q_1(70\text{–}5000\ \text{MeV}) = 2.52\cdot 10^{-26}$ photon/(atom·s·sr). The energy dependence $q_1(E_\gamma)$ in this energy range can be described by[75]

$$q_1(E_\gamma) \propto E_\gamma^{-1.8}.$$

Under the assumption that the radiation at $|b| > 5°$ is of a "local" nature, it becomes possible to determine the electron spectrum near the earth (since it can be assumed that variations in the spectrum and density of the cosmic rays over scales of hundreds of parsecs are insignificant) in an energy range which is inaccessible to direct observations because of modulation near the sun. Specifically, we are talking about electron energies $E < 1$ GeV, which are responsible for the gamma radiation of the disk in the range $E_\gamma < 100$ MeV (Fig. 1). This analysis was carried out in Ref. 74.

Characteristics of the electron spectrum at energies $E \lesssim 1$ GeV can also be found from an analysis of the diffuse radio background of the galaxy, which is a consequence of the synchrotron radiation of these particles [see expression (2.28)]. We write the electron spectrum in the form $J_e(E) = KE^{-\gamma_e}$, where K is a constant, while the spectral index γ_e may depend on the energy E. We know from radio data and from direct measurements of the cosmic-ray flux at the earth that the electron spectrum has a slope change at energies $E \sim 1$ GeV. The spectral index changes from $\gamma_e \approx 3$ at $E > 1$ GeV to $\gamma_e \approx 2.1\text{–}2.4$ at $E < 1$ GeV (Refs. 8b and 62b).

TABLE VI.

Energy range E_γ, MeV	Emissivity, 10^{-26} [sr·s·(H atom)]$^{-1}$
70—150	0.96±0.08
150—300	0.72±0.05
300—5000	0.63±0.04

Using the electron spectrum found from the radio data, we can estimate the local emissivity of the galaxy at energies $E_\gamma \approx 100$ MeV. The emissivity q_1 calculated in this manner turns out, however, to be slightly lower than that found directly from the gamma-ray data (Table VI) under the assumptions listed above. As a result, the spectrum of cosmic-ray electrons at $E < 1$ GeV reconstructed from the gamma-ray data is slightly steeper than that found from the radio data. However, as was pointed out in Ref. 74, the difference may be of minor importance in view of the uncertainty in the observational data.

In the analysis above it was assumed that the galactic gamma radiation in the direction of intermediate latitudes is of local origin, i.e., is generated exclusively by the galactic disk. However, the numerical calculations of Ref. 62e, which we discussed above, indicate the possibility of a fairly large gamma-halo flux in these directions. Is this actually true? Is there any evidence of a contribution of a gamma-ray halo to the observed flux? Apparently the first attempt to distinguish a component of high-latitude galactic radiation unassociated with the gas was undertaken in Ref. 85. The gamma-ray component which "is associated with the gas" is to be understood here as the radiation from the galactic disk due to an interaction of cosmic rays with neutral gas (atomic and molecular). Strong *et al.*[85] reported the presence in the observed flux of a gamma-ray component associated with the halo; the relative magnitude of this radiation was fairly significant for high latitudes. However, neither Strong *et al.* nor any other scientific groups have subsequently confirmed this result (at any rate, for latitudes $|b| > 30°$). There is the possibility that the reason is that the statistical significance of this result was low.

Another attempt to distinguish galactic radiation of nonlocal origin was undertaken by Bloemen *et al.*,[86] who analyzed the radiation at latitudes $|b| \lesssim 30°$. Analysis of this radiation revealed a component of the galactic radiation which was unrelated to the galactic disk (i.e., which was unrelated to either atomic or molecular hydrogen) for fairly high latitudes, $5° < |b| < 30°$ (Fig. 14b).

In our opinion, the excess radiation which was observed can indeed be related to a gamma-ray halo. It is determined by Compton scattering of relativistic electrons in the halo, since this process could explain the required gamma-ray flux according to the numerical calculations of Ref. 87 (Fig. 15). The reason why the halo component becomes important at latitudes $|b| \sim 10°$, particularly in the direction of the center, is clear from Fig. 11.

Consequently, the suggestion that the galaxy has a gamma-ray halo has experimental support.

We conclude by presenting some data on the diffuse gamma radiation in other energy ranges.

The only results available at energies $E_\gamma < 30$ MeV are from sporadic observations on satellites and balloons. Here it is possible to distinguish a low-latitude galactic radiation, which is linked with a bremsstrahlung of cosmic-ray electrons in the disk.[88] The high-latitude gamma radiation is usually assumed to be a consequence of metagalactic radiation, although we cannot rule out the possibility that here again some fraction of the flux is due to a halo. The spectrum of the high-latitude gamma radiation is shown in Fig. 11 (Ref. 81a).

So far, the interval $E_\gamma = 5$–100 GeV has not been studied at all.

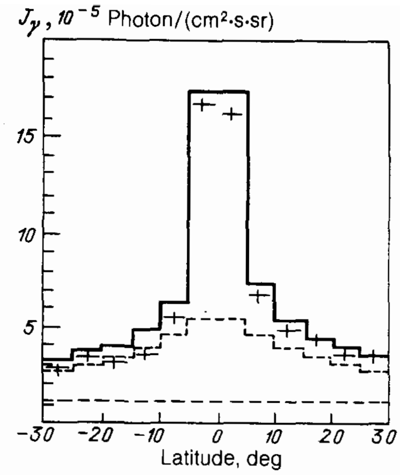

FIG. 15. Distribution of the gamma-ray intensity at energies $E_g = 300$ MeV–6 GeV in the direction of the galactic center (310°–50°) along galactic latitude.[87] Plus signs—observed intensities; dashed line—contribution of the halo due to "Compton" gamma radiation; solid line—total flux (disk + halo) of galactic radiation. The isotropic component indicated here is determined exclusively by metagalactic radiation and instrumental effects. Its value was found from Refs. 7f and 62b.

At energies $E_\gamma \gtrsim 10^{12}$ eV, gamma rays have been detected on the basis of the optical flashes (Cherenkov radiation) which they produce in the atmosphere. Detecting gamma rays is complicated by the circumstance that similar flashes are generated by the more intense isotropic flux of high-energy cosmic rays. For this reason, it is not possible to distinguish reliably the diffuse gamma radiation in this range. However, in contrast with charged cosmic rays, gamma rays propagate nearly unscattered (i.e., along a straight line). This circumstance makes it possible to detect the radiation of individual sources, including the galactic disk. The results of measurements of the fluxes in directions close to the galactic plane at $E_\gamma > 10^{12}$ eV are reported in Refs. 7d and 89. The average gamma-ray flux has been estimated to be 3×10^{-7} photon/(cm^2·sr) (Ref. 89c). Measurements have shown that the maximum radiation flux comes from directions $b \sim 5°$, not $b = 0°$. (In the energy range $E_\gamma \sim 1$ GeV, on the other hand, the flux reaches a maximum at a latitude $b \approx 0$.) It was suggested in Ref. 89a that this effect occurs because the radiation at energies $E_\gamma > 10^{12}$ eV is due to Compton losses of electrons, not the decay of π^0 mesons. The minimum of the radiation at $b \approx 0$ is due to an absorption of low-energy photons ($\varepsilon_{\rm ph} \sim 1$ eV) by dust, which results in a decrease in the intensity of the Compton radiation coming directly from the disk.

We note in this connection that according to expressions (4.13) and (4.15) the "Compton" gamma-ray spectrum is harder than the radiation resulting from the decay of π^0 mesons. It thus seems likely that the "Compton" radiation will be predominant in the overall flux at sufficiently high gamma-ray energies.

At even higher energies $E_\gamma \gtrsim 5\cdot 10^{14}$ eV, we find only a few attempts to measure the diffuse gamma-ray background.[90] Attempts are being made to distinguish lines due to primary gamma rays on the basis of the characteristics of the extensive air showers generated by the particles in the earth's atmosphere. For example, gamma rays generate showers which are muon-poor.[7d] In the experiment of Ref. 90a, eight events identified with gamma rays were detected. The radiation in this range is clearly of a galactic nature [provided, of course, that we rule out the possibility that these showers are produced by either high-energy nuclei (or protons) or secondary gamma rays formed directly in the earth's atmosphere], since the range of such gamma rays does not exceed the size of the galaxy (Table II). The flux measured in Ref. 91 was estimated to be $E_\gamma \approx (3.4 \pm 1.1)\cdot 10^{-13}\ \mathrm{cm^{-2}\cdot s^{-1}\cdot sr^{-1}}$ at $E_\gamma \gtrsim 4\cdot 10^{14}$ eV.

The nature of this radiation appears to be an open question, but Agaronyan *et al.*[91] link it with unresolved discrete sources in the local galactic neighborhood (i.e., at distances no greater than hundreds of parsecs from the earth).

Theoretical estimates of the gamma-ray flux at these energies yield the following values. The flux of galactic gamma radiation from the decay of π^0 mesons in the direction toward the galactic center is $E_\gamma \approx 10^{-13}\mathrm{cm^{-2}\cdot s^{-1}\cdot sr^{-1}}$ at energies $E_\gamma > 10^{14}$ eV (Ref. 145). If there are high-energy protons ($E \gtrsim 10^{18}$ eV) in intergalactic space, on the other hand, their interaction with the background radiation ($p + \gamma \to p + e^+ + e^-$), followed by Compton scattering of electrons by background-radiation photons, will result in the formation of an isotropic gamma-ray flux. For an observer on the earth, this flux would be characterized by a value $E_\gamma \approx 1.9\cdot 10^{-13}\ \mathrm{cm^{-2}\cdot s^{-1}\cdot cr^{-1}}$ at energies $E_\gamma > 7\cdot 10^{13}$ eV (Ref. 145a).

5. DISCRETE GAMMA SOURCES IN THE ENERGY RANGE FROM 30 MeV TO 5 GeV

Observations of discrete sources in this energy range began back in the 1960s with the first reports of the detection of a flux from some of these sources in balloon experiments (see the review by Fazio[5]). The statistical significance of such measurements was low, and the existence of some of the sources was not subsequently verified (in contrast, the existence of radiation from the Crab Nebula and the ρ-Ophiuchi molecular cloud was confirmed).

During the flight of the satellite SAS-2, a flux was detected from four sources: the Crab and Vela pulsars and the gamma sources Geminga and Cygnus X-3 (Ref. 92).

During the subsequent flight of COS-B, 25 sources were observed,[7b] of which only four could be identified. These were the Crab and Vela pulsars, which we have already mentioned, the ρ-Ophiuchi molecular cloud, and the quasar 3C 273. No known object having a significant flux in the radio, optical, or x-ray range could be detected in the directions of the other sources.

One of the most interesting results of the COS-B mission was thus the observation of a new class of sources, which emit primarily in the gamma range.

5.1. Unidentified gamma sources

The original COS-B list had 21 unidentified sources (see the refinement of this list in Refs. 93 and 94). Figure 13 shows the distribution of gamma sources with respect to galactic coordinates. According to the definition adopted by the COS-B group, a "source of gamma radiation" is an object whose flux exceeds the background by five standard deviations.

What are the properties of the unidentified gamma sources? First, we see from Fig. 13 that the overwhelming majority of the sources are galactic, since they are clustered near the galactic plane.

In addition, they have the characteristic properties listed in Table VII.

Several different models have been proposed for the unidentified sources. We might mention here the possibility (which we also mentioned in the section of this review on gamma bursts) that gamma radiation is generated in the course of accretion of matter on the surface of compact objects. Estimates show that this process could explain a luminosity of the order of 10^{34}–10^{35} erg/s in the gamma range (but see Ref. 96 in connection with this model).

The presence of one molecular cloud and two pulsars among the small number of identified sources suggests that a significant fraction of these sources are also molecular clouds or pulsars. We will discuss the characteristics of the radiation from these objects and related models below.

5.2. Gamma radiation from molecular clouds

The galactic molecular clouds are the most massive objects in the local galaxy. Their mass can reach $10^6 M_\odot$. They constitute accumulations of dense ($n_H \approx 10^2$–$10^5\ \mathrm{cm^{-3}}$), cold ($T \sim 10$–50 K) molecular hydrogen. The size of the accumulations of the clouds does not exceed about 100 pc. The degree of ionization of the gas in the clouds is low, $n_i/n_H \approx 10^{-5}$–10^{-8}. The total number of clouds in the local galaxy is a few thousand, and the total mass of molecular hydrogen is about $10^9 M_\odot$, as we have already noted.[97]

In principle, a large flux of gamma radiation can be expected from molecular clouds since one of the primary processes by which gamma radiation is generated is the interaction of cosmic rays with a gas, and the mass of gas in these clouds is large. However, there is the question of how easily cosmic rays can penetrate into the clouds, because in such a dense medium the ionization loss becomes substantial[10f]:

$$\frac{dE_k}{dt} = -7.62\cdot 10^{-9} Z^2 n_H \left(\frac{2AMc^2}{E_k}\right)^{1/2} \times\left(11.8 + \ln\frac{E_k}{AMc^2}\right)\frac{\mathrm{eV}}{\mathrm{s}}; \qquad (5.1)$$

here Ze and AM are the charge and mass of the particle, and

TABLE VII.

Angular size	$\lesssim 2^\circ$
Measured flux in the range $E_\gamma = 100$ MeV–1 GeV	$\sim (1$–$5)\cdot 10^{-6}$ Photon/(cm$^2\cdot$s)
Distance to source	2–7 kpc
Estimated luminosity in the region $E_\gamma = 100$ MeV–1 GeV	$\sim (0.4$–$5)\cdot 10^{36}$ erg/s

E_k is its kinetic energy. This problem has been taken up in several studies,[98] where it has been shown that low-energy cosmic rays with energies below a certain level (which ranges from tens of megaelectron volts to several gigaelectron volts according to various estimates) cannot penetrate deep into a cloud.

That assertion, however, would appear to contradict directly the results of an analysis of the gamma radiation from complexes of molecular clouds, which reveal no hint of any decrease in the density of cosmic rays from that in the interstellar medium.[99] Furthermore, it should be assumed for some of these clouds that the density of cosmic rays in them is higher than that between clouds.[100] It follows that a mechanism capable of transforming certain types of energy into the energy of accelerated particles must be operating in, or in the immediate vicinity of, molecular clouds.

We would first like to mention a model in which the presumed sources of cosmic rays are supernovae[101] or stars with a strong stellar wind (O and B stars),[102] which lie in or very near molecular clouds. The acceleration of particles in this case occurs at the shock fronts of the envelopes of the supernovae or of the stellar wind. The reader interested in more details regarding the mechanisms for acceleration by shock waves might look in Refs. 103. Here we will simply note that a distinguishing feature of this acceleration mechanism, which is described by the equation

$$\frac{\partial f}{\partial t}+\nabla(uf-D\nabla f)-\frac{\operatorname{div}u}{3}\frac{1}{p^2}\frac{\partial}{\partial p}(p^3f)=0 \qquad (5.2)$$

(f is the distribution function of the accelerated particles, and p is the momentum of a particle), is that power-law spectra of accelerated particles can be generated. For strong shock waves, the exponent in the power law depends on neither the velocity u nor its jump Δu at the shock front; it is also independent of the diffusion coefficient D. In this case the spectral index is a universal property, and the spectrum of accelerated particles [in the normalization

$$N(>p)=\int_p^\infty f\,d^3p)]$$

is

$$f\propto p^{-4}. \qquad (5.3)$$

According to another model, developed in Refs. 104, low-energy protons with $E_k\sim 1$ MeV which perish as a result of ionization loss generate a converging flux of Alfvén waves near a molecular cloud. These waves can interact efficiently with electrons, but of substantially higher energies, for which the ionization energy loss is unimportant. As a result, electrons with energies of the order of 100 MeV in the cloud are surrounded by a converging flux of MHD waves. In such a situation[105] the acceleration of the particles is even more efficient that the acceleration by shock fronts which we mentioned above. The electron distribution function is described by Eq. (5.2), and the spectrum of accelerated particles is

$$f\propto p^{-3}. \qquad (5.4)$$

Several questions concerning the conditions for the excitation and damping of MHD waves, incorporating the three-dimensional geometry of the problem, etc., are discussed in Refs. 98b and 106. Such a mechanism, if it does indeed operate—in general, still a questionable matter—could apparently accelerate electrons in the clouds to energies $E\lesssim 300$ MeV.

The last model which we will discuss here identifies the source of the acceleration of the charged particles as the observed turbulence of the neutral gas of the clouds (various aspects of this model are discussed in Refs. 107). According to observations, the turbulence spectrum is[108]

$$u(L)\ \mathrm{km/s}=1.1L^\alpha\ (\mathrm{pc}) \qquad (5.5)$$

for $0.01<L<10$ pc. Here u is the gas velocity at the scale of L. The parameter α is approximately 0.3–0.6. The friction force acting between the ionized and neutral components gives rise to a turbulence of the ionized gas, and the interaction of this turbulence with the magnetic field results in the excitation of random electromagnetic fields (driven MHD waves which are sustained by the turbulence of the neutral gas as driving force). The spectrum of random magnetic fields near scales $L\gtrsim L_{\min}$ is[107a]

$$H^2(L)=H_0^2\left(\frac{L_{\min}}{L}\right)^3,\quad L>L_{\min}, \qquad (5.6)$$

where $L_{\min}$ is the scale at which dissipative processes become important. The magnetic field energy $H^2/8\pi$ is thus concentrated primarily at small scales, $L\sim L_{\min}$, in contrast with the case discussed in Subsection 4.1. The nature of the motion of the charged particles depends on the relation between the Larmor radius of a particle, r_H, and the scale $L_{\min}$. If a particle is magnetized, with $r_H\ll L_{\min}$, the particles move along tangled field lines; the situation can be described as spatial diffusion. The effect of the random electromagnetic fields, on the other hand, is an acceleration of the nature of a second-order Fermi acceleration. The overall propagation of the particles in a cloud is described by an equation of the sort[107b]

$$\frac{\partial f}{\partial t}-D_x\frac{v}{c}\nabla^2 f-D_p\frac{\partial}{\partial p}p\frac{c}{v}\frac{\partial}{\partial p}(pf)=0, \qquad (5.7)$$

where D_x and D_p are the diffusion coefficients in coordinate space and momentum space, and v and p are the velocity and momentum of a particle. Under the influence of this acceleration, which is described by the coefficient D_p, power-law spectra of accelerated particles of the type

$$f\propto p^{-1}\quad\left(N(>p)=\int_p f\,dp\right)$$

are formed in a cloud. If we instead return to the normalization used above,

$$N(>p)=\int_p fp^2\,dp,$$

we find

$$f\propto p^{-3}. \qquad (5.8)$$

The acceleration of the particles continues until the Larmor radius r_H becomes comparable to $L_{\min}$. This mechanism would be ineffective in the case of unmagnetized particles. With the standard parameter values of galactic molecular clouds, this mechanism could accelerate particles, both protons and electrons, to energies of the order of 10 GeV. This mechanism could thus also explain the elevated flux of gamma radiation from molecular clouds. Furthermore, this model can explain several aspects of the spectra of positrons and antiprotons in cosmic rays[107c,d] which cannot be explained by the standard models for the origin of cosmic rays

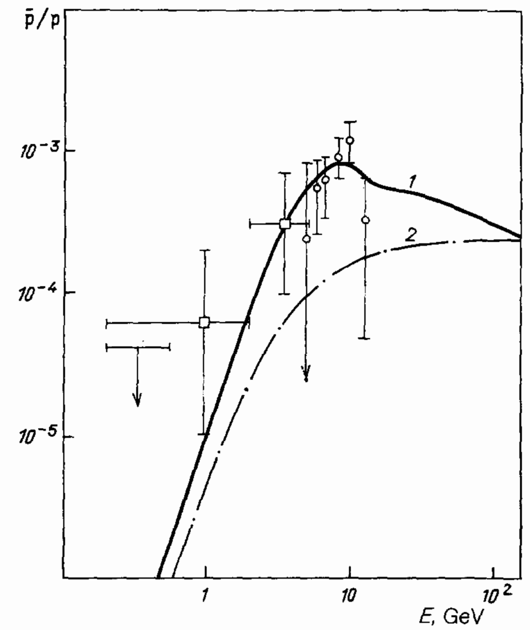

FIG. 16. Ratio of the densities of antiprotons ($\bar{p}$) and protons (p) near the earth. 1—According to the diffusion model of the local galaxy discussed in the text, with an acceleration of particles in clouds[107c,d]; 2—according to the standard diffusion model.[8b]

(curves 2 in Figs. 16 and 17). We see from these figures that the model which has particles being accelerated in molecular clouds (curves 1 Figs. 16 and 17) can provide the required intensity of antiprotons and positrons near the earth (this intensity is higher than that which would be expected on the basis of the standard model). It can also explain the corresponding observed spectral features of these particles.

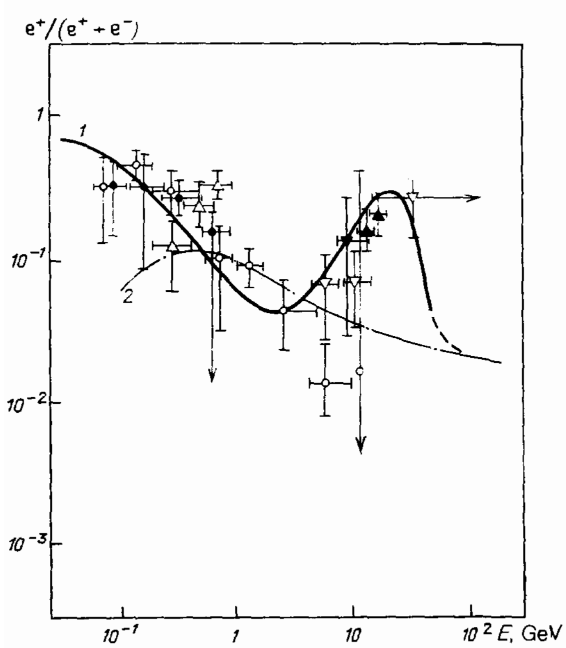

FIG. 17. Ratio of the densities of positrons (e^+) and electrons ($e^+ + e^-$) near the earth. 1—According to the diffusion model of the local galaxy, with an acceleration of particles in clouds[107d]; 2—according to the standard diffusion model.[8b]

5.3. Gamma radiation from pulsars

The presence of two pulsars (the Vela and Crab pulsars) among the identified gamma sources suggests that at least some of the unidentified sources are also pulsars. Attempts have accordingly been undertaken to observe gamma radiation from known radio pulsars[109] and also to analyze the gamma radiation from unidentified sources regarding the variability of their gamma radiation.[110]

All these attempts to link pulsars with the gamma sources in the COS-B catalog (i.e., at $E_\gamma \gtrsim 100$ MeV) have failed. In the direction of the unidentified source 2 CG 065 + 00, however, it has been found possible to detect a pulsar with a period of 6.1 ms in the radio range and also in the gamma energy range, $E_\gamma > 10^{12}$ eV (Refs. 111).

The existing data on the gamma radiation of pulsars are of course associated with studies of the Crab pulsar[112] and the Vela pulsar.[113]

The luminosity of the Crab pulsar, which has a period of 33 ms, is 65% of that of the Crab Nebula (at energies $E_\gamma > 50$ MeV). The luminosity of this pulsar in the energy interval $E_\gamma = 50$–300 MeV is $2\cdot 10^{35}$ erg/s. The radiation spectrum of the pulsar in the gamma range, $E_\gamma \approx 100$ MeV is a single power law. The spectral index of the differential flux is $\alpha_\gamma \approx 2.0$.

The radiation from the Vela pulsar has slightly different characteristics. First, nearly the entire gamma flux ($\sim 90\%$) from the Vela supernova is determined by a pulsar. Analysis of the radiation (we are talking about its pulsating component) has revealed five distinct components, with individual temporal and spectral characteristics. This result may indicate that the radiation from this pulsar is generated in different parts of its magnetosphere. The overall flux from Vela cannot be described by a single power law. The gamma luminosity of Vela in the range from 50 MeV to 10 GeV is estimated to be $4\cdot 10^{34}$ erg/s.

So far, the theoretical models[114–116] cannot explain the entire spectrum of gamma radiation from tens of megaelectron volts to 10^{12} eV. The models which have been constructed link this radiation with synchrotron, Compton, and curvature energy losses of electrons in the strong magnetic fields of the magnetospheres of pulsars, but any single model succeeds in explaining only certain intervals of the observed spectrum.

The luminosity in the gamma range from rapidly rotating pulsars could easily be of the order of 10^{36} erg/s, according to theoretical predictions.[114–116] In general, however, the processes by which the spectra of accelerated particles are formed in the magnetospheres of pulsars and by which electromagnetic radiation is generated in the various wavelength ranges constitute a separate and large problem, several aspects of which are set forth in the reviews of Ref. 116.

Another possibility is that some of the unidentified gamma sources are rapidly rotating white dwarfs.[153]

5.4. Radiation from supernovae

Analysis of the gamma radiation from supernovae is interesting because these objects are regarded as the primary sources of cosmic rays in the local galaxy. In contrast with the radiation from supernovae at $E_\gamma \sim 1$ MeV which we were discussing above, and which is generated as a result of the β decay of ^{56}Co, the gamma radiation at energies $E_\gamma \sim 100$ MeV, which is not associated with a pulsar, is apparently generated as a result of the interaction of cosmic rays generated by this star with the gas of the surrounding envelope. In the early stages of the evolution of a supernova, the generation of cosmic rays is probably associated with either a pulsar which is formed in the interior or an acceleration of particles by random electromagnetic fields (second-order Fermi acceleration) which are excited behind the shock fronts of the envelope and also directly at a shock front.

The supernova which occurred on 23 February 1987 (SN1987A) in the Large Magellanic Cloud is of particular interest in connection with the discussion above. Since 1604, when the Kepler supernova was observed, SN1987A is the first supernova which has been seen with the unaided eye from the earth. By virtue of its comparative proximity (it is about 55 kpc away), it is quite possible in principle that we could study the gamma radiation from SN1987A. Taking this path, one might determine in which stages of the evolution of a supernova most of the cosmic rays are accelerated: Are they formed directly after the explosion, or are they generated a certain time later, at the shock fronts of envelopes which have formed?

Let us examine the characteristics of the gamma radiation from a supernova which would be generated by particles accelerated at a shock front.[117] When the envelope of a supernova is ejected, a thin shell of compressed gas forms at its periphery.[118] On its outer side, this shell is bounded by a shock wave, which propagates along the stellar wind left by the presupernova; on its inner side, it is bounded by a rarefaction wave. In the rest frame of the shell, gas flows into the shell across the inner and outer shock fronts. At both of these fronts, the particles are accelerated by a first-order Fermi mechanism. A distinctive feature of this acceleration is that it occurs in converging gas flows, which are flowing into the shell. Since accelerated particles are carried by the gas flows, these particles are to be found within a shell. Behind the shock fronts the density of accelerated particles decreases exponentially over a length scale $l \sim D/u$, where D is the diffusion coefficient of the accelerated particles, and u is the gas flow velocity. The accelerated particles and the gas are thus concentrated in the outer shell, which is accordingly a fairly intense source of gamma radiation, with energies from about 100 MeV to 10–100 GeV. The total number of gamma rays (most of which have energies in the interval 70–100 MeV) emitted by the shell per unit time is[117]

$$Q_\gamma^{\text{tot}} \approx \frac{10(k-3)\sigma_0}{64\pi m_N c u_W} \beta \frac{R(t)}{t^2} \dot{M}^2, \qquad (5.9)$$

where k is the spectral index in the expression for the density as a function of the distance, $\rho \propto r^{-k}$, for the outer edge of the inner shell ($k \approx 10$); $\sigma_0 = 3.2 \cdot 10^{-26}$ cm^2 is the pp cross section used for normalization; m_N is the mass of a nucleon; u_W is the wind velocity ($u_W \approx 10^6$ cm/s); β is the fraction of the kinetic energy of the gas which is converted into the energy of the accelerated particles when a shock front is crossed ($\beta \approx 0.1$); $\dot{M}$ is the mass loss of the presupernova ($\dot{M} \sim 10^{-7}\, M_\odot$/yr for SN1987A; $\dot{M} \sim 10^{-5}\, M_\odot$/yr for a typical presupernova—a red giant); and $R(t)$ is the distance from the center to the outer shell at time t. The radius of a shell can be written

$$R(t) = Br_f \left(\frac{t}{t_f}\right)^\alpha,$$

where B is a dimensionless parameter of the hydrodynamic solution, whose characteristic value is 1–2, $r_f = 1 \cdot 10^{16}$ cm, $t_f \approx 1 \cdot 10^7$ s, and $\alpha = 0.8$–0.9. It follows from (5.9) that the physical parameter which primarily determines the total flux of gamma radiation is the rate at which the presupernova loses mass, $\dot{M}$. For SN1987A, this rate is low, so the expected flux of gamma radiation at the earth could not be detected:

$$F_\gamma^{\text{tot}} \approx 1 \cdot 10^{-9} \left(\frac{t}{10^7\,\text{s}}\right)^{-1.1} \text{cm}^{-2} \cdot \text{s}^{-1}.$$

For an ordinary supernova occurring at the center of the local galaxy, the flux would be $F_\gamma^{\text{tot}} \approx 1 \cdot 10^{-4}(t/10^7\text{s})^{1.1}$ cm$^{-2}\cdot$s^{-1}. Such a flux could be detected with very simple detectors.

The gamma radiation from the outer shell has some characteristic features which would allow one to distinguish it from the gamma radiation from the inner shell: The gamma radiation with $E_\gamma \sim 100$ MeV should appear a few days after the supernova explosion, while the radiation from the inner shell should appear only after its bleaching, i.e., after several months. The gamma radiation from the inner shell would be accompanied by x-ray and radio emission.

We turn now to the acceleration of particles within an envelope (the sources of the particles are pulsars or an acceleration by internal turbulence) and to the generation of gamma radiation.

The luminosity of a supernova in the gamma-ray range in its early stage of development was studied in Refs. 119. We will make some estimates pertinent to SN1987A. These estimates are made under the assumption that there is a source of cosmic rays with a luminosity L_p inside the envelope. The gamma radiation from the supernova becomes observable when the envelope becomes transparent to gamma rays.

For photons with energies $E_\gamma \gtrsim 70$ MeV this "bleaching" occurs a few months or so after the explosion. At $L_p \approx 10^{41}$ erg/s, for example, the flux of such gamma rays would be $(3\text{–}6) \cdot 10^{-5}$ photon/cm$^2\cdot$s) in order of magnitude—well above the sensitivity of the Gamma–1 telescope $[\sim 2 \cdot 10^{-7}$ photon/(cm$^2\cdot$s)$]$.

At approximately the same time as for $E_\gamma \sim 70$ MeV or slightly later, the envelope becomes transparent to gamma rays with energies $E_\gamma \gtrsim 10^{12}$ eV and $E_\gamma \gtrsim 10^{15}$ eV.

Note that under the conditions corresponding to an expanding envelope the gamma-ray flux from a supernova will fall off fairly rapidly, and the "live time" for observing radiation from the supernova may be no more than a few years.

Consequently, there is an extremely urgent need to carry out studies without delay—right now. We have only a limited time available for observations, and the explosion of the next suitable supernova may be several hundred years in the future.

In a sense, the explosion of SN1987A occurred at an unfortunate time, and not in the best spot. The timing is extremely unfortunate because at the moment there are no gamma-ray satellites in orbit, so observations in the range $E_\gamma \sim 100$ MeV cannot be carried out from satellites (the need for a patrol service in the gamma-ray range was pointed out, in particular, in Ref. 120).

The place where the explosion occurred is unfortunate because it is in the southern part of the sky, while most of the telescopes are in the earth's northern hemisphere [we are talking about measurements in the radio, optical, and gamma-ray ranges (with $E_\gamma > 10^{12}$ eV and $E_\gamma > 10^{15}$ eV)].

Nevertheless, attempts are being made to measure the flux of gamma radiation from SN1987A. On 19 April 1987 and 5 April 1988, for example, the radiation flux in the range 50–500 MeV was measured on balloons. All that could be established were upper limits: $F_\gamma < 2.9\cdot 10^{-5}$ photon/(cm^2·s) and $F_\gamma < 9\cdot 10^{-4}$ photon/(cm^2·s), respectively.[121] In November 1987, a measurement of the flux from SN1987A yielded only the upper limit $F_\gamma < 2.3\cdot 10^{-11}$ photon/cm^2·s) at energies $E_\gamma < 10^{12}$ eV (Ref. 149). Later on, however, in May 1988, there were reports of the detection of radiation from this supernova at energies $E_\gamma > 3\cdot 10^{12}$ eV with a flux $F_\gamma \approx 2\cdot 10^{-11}$ photon/(cm^2·s) (Ref. 122; the latter result requires confirmation).

Our future hopes are pinned on the launch of the Soviet-French satellite Gamma and the US observatory GRO.

5.5. Binary galactic gamma sources

Let us look at some data on two puzzling sources of gamma radiation, Cygnus X-3 and Geminga, whose existence and nature are the subjects of a continuing debate.[94,123,129]

Gamma radiation from the variable x-ray source Cygnus X-3, which is a binary system with a period of 4.8 h, was detected in 1972, in two gamma-ray energy ranges simultaneously: $E_\gamma > 40$ MeV and $E_\gamma > 10^{12}$ eV (Ref. 123a). The flux in the energy range $E > 40$ MeV turned out to be $E_\gamma \approx (6.4 \pm 2.7)\cdot 10^{-5}$ photon/(cm^2·s) on the average. The radio and gamma-ray data made it possible to estimate the distance to the source: about 10 kpc. It thus became possible to estimate the luminosity of Cygnus X-3 in the gamma-ray range $E_\gamma \gtrsim 10^{15}$ eV: $L_\gamma \sim 10^{37}$–10^{38} erg/s. This figure represents a significant fraction of the luminosity of the entire galaxy in the gamma-ray range (see the review by Vladimirskiĭ *et al.*[123a] regarding the source Cygnus X-3).

Recent observations on the satellite SAS-2 have confirmed a pulsating radiation with a period of 4.8 h from Cygnus X-3, but the measured flux has turned out to be about a third of that given above.[124]

The satellite COS-B detected no radiation at all from Cygnus X-3 at the level $F_\gamma < 3\cdot 10^{-6}$ photon/(cm^2·s) (Ref. 125). Furthermore, whether radiation from Cygnus X-3 was detected on the satellite SAS-2 has been placed in doubt (Refs. 123b,c); the group that carried out that experiment does not agree with the criticism.[123d]

One possible explanation for such contradictory data is that there are long-period variations in the radiation from this source.[123a,b] As a result, there may be periods of "favorable" and "unfavorable" phases in the observation of Cygnus X-3. Information about the variability of the radiation from this source will be given in §6 below.

The Geminga source ranks second, after Vela, in terms of the measured intensity in the gamma range $E_\gamma \sim 100$ MeV (Ref. 7b). Its radiation in other wavelength ranges, in contrast, is insignificant. Attempts to observe a significant flux in the radio range in the direction of this source have not succeeded. Nevertheless, the existing optical and x-ray data have served as a basis for several suggestions regarding an association of Geminga with one object or another in other radiation ranges.[94,126]

Important to an identification of Geminga were reports of the observation of a variability of its radiation with a period of 59 s in the gamma and x-ray ranges.[94] These data served as the basis for the construction of models of the Geminga source, as a close binary system consisting of two neutron stars[127] or a white dwarf and a black hole.[128]

Buccheri *et al.*,[129] however, have cast doubt on the very existence of the 59-s period in the gamma radiation from Geminga. All we can do here is repeat that further research is required in the gamma-ray range.

5.6. Extragalactic gamma-ray sources

We have already mentioned the observation of extragalactic gamma-ray sources: the galaxies NGC 4151 (Ref. 130) and CenA (Ref. 131) and the quasar 3C 273 (Ref. 7b). Of particular interest for the problem of the origin of cosmic rays, however, is the gamma radiation of the galaxies closest to us: the Large and Small Magellanic Clouds (LMC and SMC) and the Andromeda Nebula (M 31). The reason is that if the cosmic rays are of metagalactic origin their density in these galaxies should be the same as that at the earth (if we ignore contributions from local sources).

In the metagalactic models it is a simple matter to estimate the expected flux of gamma radiation, once we find the gas distribution in these galaxies from radio data. Estimates for the Large and Small Magellanic Clouds yield the fluxes[132]

$$F_\gamma^{\rm LMC}\ (E_\gamma > 100\ {\rm MeV}) \approx 2\cdot 10^{-7}\ {\rm photon/(cm^2\cdot s)},$$
$$F_\gamma^{\rm SMC}\ (E_\gamma > 100\ {\rm MeV}) \approx 1\cdot 10^{-7}\ {\rm photon/(cm^2\cdot s)},$$

while for M 31 the estimate is[133]

$$F_\gamma^{\rm M31}\ (E_\gamma > 100\ {\rm MeV}) \approx 2.4\cdot 10^{-8}\ {\rm photon/(cm^2\cdot s)},$$

If we compare these estimates of the fluxes with the sensitivity of the Gamma I and GRO telescopes, we see that such measurements can be carried out. A deviation from these estimates of F_γ would indicate a galactic origin of the cosmic rays, since a nonuniform cosmic-ray density in metagalactic space would contradict the metagalactic models.

6. GAMMA RADIATION AT HIGH ENERGIES ($E_\gamma > 10^{12}$ eV and $E_\gamma > 10^{15}$ eV)

The two energy ranges $E_\gamma > 10^{12}$ eV and $E_\gamma > 10^{15}$ eV are singled out because of the particular methods by which gamma rays are detected (see the Introduction). The reader interested in more details on research of these energies might look in Refs. 7d,g and 134.

It was suggested in Refs. 135a,b that the Cherenkov optical radiation generated by particles (and, in particular, by gamma rays) be measured. The first systematic observations at energies $E_\gamma > 10^{12}$ eV were undertaken in the USSR in 1960 (Refs. 135c,d). Those observations, however, yielded no statistically significant results on the gamma-ray fluxes from several sources. Other detectors were subsequently developed for measuring the radiation at $E_\gamma > 10^{12}$ eV (on the basis of flashes of Cherenkov radiation in the earth's atmosphere). As a result, a gamma-ray flux ($E_\gamma > 10^{12}$ eV) was detected from several sources. Data on these sources are listed in Table VIII (here and below, 1

TABLE VIII.

Source	Period, ms	Flux, $cm^{-2} \cdot s^{-1}$	Distance, kpc	Luminosity, erg/s
Pulsars:				
Crab	33	$4 \cdot 10^{-12}$	2.0	$6 \cdot 10^{33}$
Vela	89.2	$3 \cdot 10^{-12}$	0.5	$3 \cdot 10^{32}$
PSR 1937+21	1.56	$2 \cdot 10^{-11}$	5	$2 \cdot 10^{35}$
PSR 1953+29	6.13	$1.2 \cdot 10^{-12}$	3.5	$6 \cdot 10^{35}$
PSR 1802—23	112	$2.3 \cdot 10^{-10}$	2.7	$3 \cdot 10^{35}$
Binary x-ray sources:				
Cygnus X-3		$5 \cdot 10^{-11}$	11.4	$3 \cdot 10^{36}$
Her X-1		$3 \cdot 10^{-11}$	5	$3 \cdot 10^{35}$
4 U 0115+63		$7 \cdot 10^{-11}$	5	$6 \cdot 10^{35}$
Vela X-1		$2 \cdot 10^{-11}$	1.4	$2 \cdot 10^{34}$
Supernova remnants:				
Crab Nebula		$1 \cdot 10^{-11}$	2	$2 \cdot 10^{34}$
SN1987A ($E_\gamma > 3$ GeV)		$2 \cdot 10^{-11}$	50	10^{38}
Radio galaxies:				
Cen A		$4 \cdot 10^{-12}$	4400	$3 \cdot 10^{40}$

Data from the review in Ref. 7d

TeV = 10^{12} eV; 1 PeV = 10^{15} eV).

Incidentally, the "thresholds" which we have reported here, $E_\gamma \sim 10^{12}$ eV for observations based on Cherenkov radiation and $E_\gamma \sim 10^{15}$ eV for observations based on extensive air showers, are a bit arbitrary. For example, large telescopes might make it possible to lower thresholds $E_\gamma \sim 10^{12}$ eV to about $E_\gamma \sim 10^{11}$ eV.

In addition to the sources listed in Table VIII, there are contradictory indications of a detection of gamma radiation at $E_\gamma \gtrsim 10^{12}$ eV from the pulsars PSR 0950 and PSR 1133, the Geminga source, the galaxy M 31, and the galactic disk.

At higher energies, $E_\gamma \gtrsim 10^{15}$ eV = 1PeV, gamma rays are detected on the basis of the extensive air showers which they generate, which have some distinctive features. The sources and their characteristics are listed in Tables IX and X.

Of greatest interest in this gamma-ray range is the source Cygnus X-3, whose luminosity is higher than that of any other galactic source.

The differential radiation spectrum from this source can be described by a single power law with an index $\alpha_\gamma \approx 2.1$ over a wide range of photon energies. There are indications of the existence of a number of periods in the radiation from Cygnus X-3. In addition to the period of 4.8 h there are apparently periods of 19.2 day, 34 day, and 328 day (Refs. 7d and 136). It is important to note that pulsations with periods of 12.6 ms (Ref. 7d) and 9.22 ms (Ref. 137) have been observed in the emission spectrum. These pulsations may be evidence that the binary system of Cygnus X-3 includes a millisecond pulsar. If these observational results are correct (and this is still an open question), the model proposed previously[138] for the source Cygnus X-3 would acquire some very strong observational support. According to that model, Cygnus X-3 is a binary system including a fast pulsar. The pulsar injects cosmic rays, whose interaction with the matter in the atmosphere of the massive component of the binary system results in the generation of gamma radiation.

The observed gamma radiation from Cygnus X-3 could hardly be explained as an emission by electrons due to their rapid energy loss in the magnetic fields of a neutron star. The gamma rays with the observed energies are apparently generated in an interaction of accelerated protons with gas nuclei through the production and decay of π^0 mesons. Working from this model, we can estimate the "luminosity" of this source in terms of cosmic rays (i.e., essentially the proton luminosity)[139]:

$$L_p = 1.8 \cdot 10^{40} \frac{F_\gamma (E_\gamma > 10^{15}\ \text{eV})}{1.6 \cdot 10^{-13}\ \text{cm}^{-2} \cdot \text{s}^{-1}} \frac{\Omega}{4\pi} \left(\frac{r}{13\ \text{kpc}} \right)^2 \cdot \frac{0.1}{\tau_\gamma T}\ \text{erg/s}, \tag{6.1}$$

TABLE IX.

Source	Threshold energy E_γ, PeV	Flux, $cm^{-2} \cdot s^{-1}$	Distance, kpc	Luminosity, erg/s
Binary x-ray sources:				
Cygnus X-3	1	$2 \cdot 10^{-14}$	11.4	$6 \cdot 10^{36}$
Her X-1	0.5	$3 \cdot 10^{-12}$	5	$2 \cdot 10^{37}$
Vela X-1	3	$9 \cdot 10^{-15}$	14	$2 \cdot 10^{34}$
LMC X-4	10	$5 \cdot 10^{-15}$	50	10^{38}
Supernova remnants:				
Crab Nebula	1	$1 \cdot 10^{-13}$	2	$2 \cdot 10^{35}$
Binary source with black hole (?):				
Cygnus X-1	1	$5.4 \cdot 10^{-13}$	2	10^{36}

Data from Refs. 7d, g and 154.

TABLE X. Temporal characteristics of binary sources.

Source	Period of pulsar	Orbital period of binary system	Precession period, day
Cygnus X-3	12.59 ms (?) 9.22 ms	4.8 h	19.2 (?) 34 (?)
Her X-1	1.24 s *)	1.7 day	35
4 U 0115+63	3.61 s	24 day	
Vela X-1	283 s	8.974 day	
LMC X-4	13.5 s	1.4 day	30.5
Cygnus X-1		5.6 day	

Data from the reviews in Refs. 7d, g and 142.

*) The source Her X-1 has an interesting feature: The period of the gamma emission of the pulsar in this source is slightly shorter than the period of its emission in the x-ray range.[7d]

where Ω is the solid angle into which the proton beam is emitted, $T = 4.8$ h is the orbital period, τ_γ is the time over which the protons bombard the target with the thickness which is the optimum thickness for the generation of gamma rays, and F_γ is the radiation flux from Cygnus X-3 at energies $E_\gamma > 10^{15}$ eV which is observed at the earth.

The proton luminosity of Cygnus X-3 estimated from expression (6.1) might range up to 10^{40}–10^{41} erg/s. It follows that sources of this type (Cyg X-3 and Her X-1) can inject a significant fraction of the galactic cosmic rays. We recall that the luminosity of the local galaxy in terms of cosmic rays is 10^{40}–10^{41} erg/s (Ref. 8b, for example).

Note, however, that the radiation from Cygnus X-3 cannot itself be regarded as a solidly established fact (see Ref. 140 in this connection). The same caveat applies to other discrete gamma sources in this energy range. Essentially all are observed at a level of 3σ; a final resolution of the question of their existence may emerge from future experiments. In this connection we note that there are several plans for installations for $E_\gamma > 10^{11}$–10^{15} eV (Ref. 141; see also the reviews in Refs. 7d, g).

7. CONCLUDING REMARKS

We have been discussing the results which have been found in gamma-ray astronomy and some problems facing it. Our hopes for the near future are pinned on the launches of the satellites Gamma and GRO (which are to detect photons with energies from tens of megaelectron volts to tens of gigaelectron volts) and also the development of new ground-based installations for detecting photons with energies $E_\gamma \gtrsim 10^{12}$ eV and $E_\gamma \gtrsim 10^{15}$ eV. To some extent or other, these energy ranges have already been utilized, although the measurements are still very inadequate. A further and harmonious development of gamma-ray astronomy will not be possible without an expansion of the energy range in which the research is carried out (see Table I). Two projects are noteworthy here: GRASP (Ref. 55) and Gamma-400 (Ref. 143). These projects might solve the problem. The implementation of the first of these projects would make it possible to "connect" the well-studied x-ray range with the gamma-ray range. The second project is intended for studying the region from a few gigaelectron volts to hundreds of gigaelectron volts—a region which has not previously been studied at all. The need for these projects is obvious, and delays in their realization may hold up the development of gamma-ray astronomy and of astrophysics in general.

It is hardly necessary to stress that the need is no less urgent for more-accurate and statistically sound data in the gamma-ray ranges in which observations have already begun.

In particular, we would like to call attention to a paper by Cassiday *et al.*[155] They reported the possible observation of neutral particles of some sort with an energy above $5 \cdot 10^{17}$ eV emitted from the source Cygnus X-3. At such energies, even neutrons might be able to make it to the earth from Cygnus X-3. For this reason, Cassiday *et al.*[155] discuss "neutral particles," not specifically gamma rays, as would usually be discussed. Note that also at lower energies, $E > 10^{12}$ eV, the nature of the neutral radiation arriving from the cosmic sources has not been solidly established.[156] Yet a further difficulty is that, as we have stressed in the text above, it has not yet been possible to put all doubts aside that neutral radiation with $E > 10^{15}$ eV has been detected reliably at all.

There is no doubt that each step down the path toward making use of the gamma-ray range will lead us to new problems, whose resolution will make possible progress in research on the processes which are occurring in the universe. The particular interest of the authors of the present paper is to use gamma-ray-astronomy data to solve several questions concerning the problem of the origin of cosmic rays.

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NOTATION

m	mass of electron, $m = 9.108 \cdot 10^{-28}$ g
M	mass of proton, $M = 1.672 \cdot 10^{-24}$ g
e	charge of electron, $e = 4.803 \cdot 10^{-10}$ cgs
c	velocity of light, $c = 2.9979 \cdot 10^{10}$ cm/s
k	Boltzmann's constant, $k = 1.380 \cdot 10^{-16}$ erg/grad

$\left.\begin{matrix} r \\ x \end{matrix}\right\}$ radiation change, radio or x-ray

E_k kinetic energy of particle

E energy of particle

p momentum of particle

γ spectral index of particles

α spectral index of radiation

n density of particles

ε_{ph} energy of low-energy photons

ν frequency of radiation

r_H Larmor radius of relativistic particles

ρ,z cylindrical coordinates; in this case, ρ is the coordinate (radius) along the galactic disk, and z is the coordinate perpendicular to the disk

$M_\odot$ mass of sun, $M_\odot = 1.99\cdot 10^{33}$ g

[1)]The lower boundary of the gamma-ray range is ordinarily put at $E_\gamma = 10^5$ eV. In addition, some softer radiation emitted by nuclei is also called "gamma radiation."

[2)]We are talking about the loss of photons from the primary beam, so scattering is equivalent to absorption.

[3)]See Ref. 148b and the bibliography there regarding pair production in strong magnetic fields.

[4)]The local galaxy and, generally speaking, other galaxies also have halos of various types: a stellar halo, a gaseous halo, a cosmic-ray halo, and a gamma-ray halo.[68]

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