Gamma rays and the structure of the Galaxy

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The observations and theoretical interpretations of galactic γ rays in the energy region 10^7–10^{10} eV are reviewed. Galactic γ rays consist of a diffuse component and radiation from discrete sources. The diffuse component, which is formed as the result of interaction of cosmic rays with interstellar gas, reflects the large-scale structure of the Galaxy. Recent observations have revealed the existence of a belt of molecular hydrogen at a distance 4–8 kpc from the Galactic Center and indicate a nonuniformity of the distribution of cosmic rays over the disk and in the halo of the Galaxy. Information on the small-scale structure of the Galaxy in the γ region is obtained from the discrete γ-ray sources, of which more than twenty have now been observed. The best known of these are the pulsars in the Crab Nebula, Vela-X, Cygnus X-3, and the region of the Galactic Center. Possible mechanisms for the γ radiation of discrete sources are discussed.

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CONTENTS

1. INTRODUCTION

Contemporary astronomy is performed at all wavelengths. Observations are now carried out in all regions of the electromagnetic spectrum without exception, from radiowaves to ultrahard γ rays ($E_\gamma \sim 10^{12}$ eV). Frequency regions which only recently were blank spots have been successfully mastered by means of extra-atmospheric methods of observation: high-altitude balloons, satellites, space ships. A consequence of this all-wave nature of the observations has been a comprehensive approach to the study of astrophysical objects. A brilliant example is in the investigations of the Galaxy carried out recently by means of optical, radio, infrared, and (the area which has produced the most interesting and new results) γ astronomy. It is γ radiation which has provided new astrophysical information on such familiar objects as the Galaxy as a whole and its individual structural units: stars, interstellar gas, cosmic rays. The present review is devoted to the observational data on galactic γ rays and their theoretical interpretation, which add greatly to the previous ideas on the structure and composition of the Galaxy.

2. DIFFUSE GALACTIC γ RAYS (GGR)

The principal results in the study of galactic γ rays have been obtained in two experiments carried out on specialized satellites, each intended for only a single problem: SAS-2 (the Small Astronomical Satellite No. 2 of the Goddard Space Flight Center in the USA) and COS-B (the second space laboratory of the European organization ESA). Instruments working on board satellites are typical in their dimensions and resolution of the second-generation γ telescopes which began to be used at the end of the 1960s and at the present time are already leaving the scene and yielding to im-

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proved instruments.

a) The experiment on SAS-2

SAS-2 was a satellite of small size and weight with stabilization of rotation and magnetic orientation.[1,2] The axis of the apparatus, which coincided with the twist axis of the satellite, could be oriented toward any point of the sky with an accuracy of 0.3°. The direction of orientation was determined by three independent detectors: a solar detector, a three-axis magnetometer, and a stellar photometer.

The satellite was placed in a low orbit with an apogee 610 km, a perigee 440 km, an inclination angle of 2°, and a period of rotation 95 min. The orbit, which was almost circular and almost equatorial,1) passed under the inner radiation belt in the region least accessible for cosmic rays which are deflected by the Earth's magnetic field. As a result a comparatively low background from charged particles was observed in the apparatus. This low orbit also had the disadvantage that a portion of the sky observed was periodically blocked by the Earth. A telescope recorded cosmic γ rays on the average 45% of the time, and for the remaining time it received γ rays reflected by the Earth.

Two tape recorders recorded information from the γ telescope at a rate of 1 kilobit/sec (two thirds of the recorded information consisted of track coordinates in the wire spark chamber). Transmission of information by telemetry to the tracking station was carried out at a rate of 20 kilobits/sec. Within the range of visibility of the ground station, direct transmission of information from the apparatus was also carried out, which permitted the experimenters to obtain operating information and also to tie the satellite clock to universal time with an accuracy of ±1 msec.

Observations on the SAS-2 were carried out continuously for half a year (instead of the planned year of operation) from November 1972 to June 1973, when they were stopped as the result of a failure in the power system. During this time the telescope scanned more than half of the celestial sphere and for the first time the region located along the Milky Way, with a one-week exposure of each portion of the sky.

The γ telescope in SAS-2, shown schematically in Fig. 1, recorded γ rays with energies $E_\gamma \geq 30$ MeV (the detection threshold was determined by the amount of material in the telescope). The total viewing angle at half-height of the instrumental function (FWHM), which can be considered the aperture of the apparatus, was 35°. The effective area of the telescope was 640 cm^2.

The heart of the apparatus consisted of a 32-layer wire spark chamber with ferrite cores, the upper portion of which (16 layers) served as a γ-ray converter. The picture of an event in the spark chamber permitted it to be treated practically without ambiguity as a γ-ray event (the characteristic conversion V beginning in one of the chamber layers) and permitted measurement of the angle at which the γ ray entered the apparatus. From the spatial orientation of the apparatus it was possible to determine the celestial coordinates of the point from which the γ ray arrived. Multiple scattering of the components of the conversion pair smeared the point into a circle whose size was determined by the γ-ray energy and which characterized the angular resolution of the telescope; at an energy $E = 100$ MeV this was ~4°. This value is very large in comparison with present-day optical and radio telescopes; however, if we recall the history it is comparable with the angular resolution of the radio telescopes of the 1940s. With this angular resolution and week-long observation periods the minimum measurable flux from a discrete source which could be identified in an isotropic background amounted to $\sim 10^{-6}$ photons/cm^2 sec.

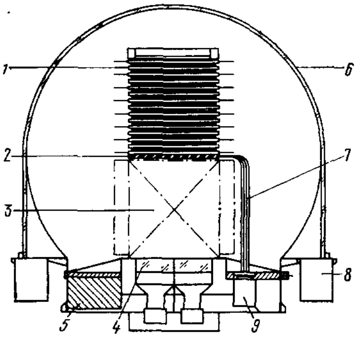

FIG. 1. Physical block diagram of the SAS-2 γ telescope[2]: 1—upper wire spark chamber, 2—scintillation counter, 3—lower spark chamber, 4—Čerenkov counters (four units), 5—electronics, 6—anticoincidence counter, 7—light pipe, 8—anticoincidence counter photomultipliers (8 units), 9—coincidence counter photomultipliers (4 units).

Gamma events were distinguished from the flux of cosmic rays incident on the apparatus by means of scintillation and Čerenkov counters connected in coincidence and anticoincidence. Anticoincidence counter A, constructed of a plastic scintillator in the form of a dome, covered the apparatus and removed the background from cosmic-ray charged particles. Its efficiency was very high, amounting to 0.99999, which together with the low intensity of cosmic rays in the selected orbit practically removed spurious triggerings of the apparatus.

In addition to γ rays the apparatus recorded charged particles both with individual counters and with combinations of counters, which provided important material for analysis of the results.

The weight of the γ telescope and its average power consumption were 85 kg and 10 watts.

b) The experiment on COS-B

The satellite COS-B was launched 9 August 1975. Three days later the γ telescope was turned on and began to work.[3,4] According to the initial plan, observations were to be carried out for two years from

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1)To achieve this orbit, the launch was made from the proving ground at San Marco, Kenya, which is near the equator. The satellite SAS-1 (Uhuru), which provided a whole epoch in x-ray astronomy, was launched from the same spot in 1970.

August 1975 to August 1977. During this time it was decided to extend the operation of the telescope to the end of 1978. At the time of this writing (February 1979) the experiment is being successfully continued and a record has been established for the length of operation on a spark γ telescope in a satellite orbit.

The satellite consists of a cylinder of diameter 1.4 m and length 1.13 m in which the telescope is arranged along the axis (Fig. 2). COS-B was placed in a highly excentric orbit with a perigee varying from 300 to 3000 km, an apogee ~100 000 km, and a period of revolution of 36 hours and 44 minutes. The γ telescope spends 95% of its time beyond the dangerous portions of the magnetosphere which are filled with captured radiation. During this time it is practically unshadowed by the Earth, which gives a gain of a factor of two in efficiency of observation in comparison with SAS-2.

In the size and weight of the satellite (~280 kg) and of the apparatus (~120 kg), in the accuracy of orientation and stabilization, and in many instrumental respects (γ-ray energy range, effective area, etc.) the experiment carried out in COS-B is similar to that of SAS-2. It also is intended first of all to study galactic γ radiation; it also utilizes a multilayer wire spark chamber with ferrite-core memory. However, a number of improvements have also been provided which permit COS-B to obtain more detailed information on the γ radiation of the Galaxy:

1) The exposure of each portion of the sky was increased to a month. When the angular resolution (~5° at 100 MeV), the background, and the efficiency of the apparatus are taken into account, this leads to a minimum measurable[2] flux 3×10^{-7} photons/cm^2 sec.

2) The apparatus includes a scintillation calorimeter employing a CsI(Tl) crystal 4.7 radiation lengths thick. This permits measurement of the energy spectra of γ-ray fluxes up to several GeV. In addition, as a result of the transition to higher energies the accuracy in spatial resolution of directional γ-ray fluxes is improved.

3) In parallel with the γ telescope there is a proportional counter with a slit collimator whose angular resolution is 1.1° for measurement of x rays with energy 2–12 keV. It serves as a synchronizer in the search for x rays and γ rays, particularly in the search for γ rays from x-ray pulsars. The time of arrival of x rays and γ rays in terms of the satellite clock is measured with an accuracy 0.2 msec.

c) Results of observations. Spatial distribution of GGR intensity

The flux of cosmic γ rays from the Milky Way was first observed in 1967 by the satellite OSO-3 (Orbiting Solar Observatory No. 3),[5] and following this it was measured in a number of observations with high-altitude balloons.[6-11] The experiments of SAS-2 and COS-B substantially extended the information on GGR, which enabled observers to learn its nature and to use it as a tool for study of the structure of the Galaxy.

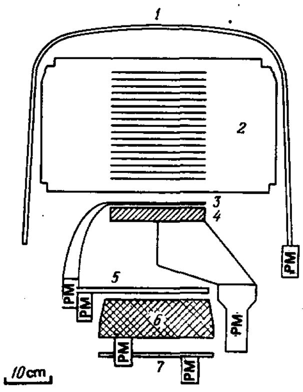

FIG. 2. Block diagram of COS-B γ telescope.[4] 1—anticoincidence counter, 2—spark chamber, 3—5—counters controlling telescope, 6—calorimeter, 7—high-energy-particle counter.

For γ-ray energies of tens and hundreds of MeV the GGR is dominant over the isotropic diffuse background. In Fig. 3 we have shown the distributions of the intensity of GGR as a function of galactic latitude at two places in the Milky Way: in the region of the Galactic Center (the interval of galactic longitudes $-30° \leq l^{II} \leq 30°$) and in the region of the Galactic Anticenter ($160° \leq l^{II} \leq 200°$). The GGR exceeds the isotropic background by a factor of 20 in the region of the center and by a factor of 4 in the region of the anticenter. In discussing the latitude distributions it is necessary to take into account the intrinsic angular resolution of the telescope, which is of the same order as the half-width of the distributions. Analysis shows, however, that the observed widths cannot be explained only by the instrumental resolution. There is also an astrophysical cause: a certain number of γ rays arrive from the near portions of the Galaxy, which are re-

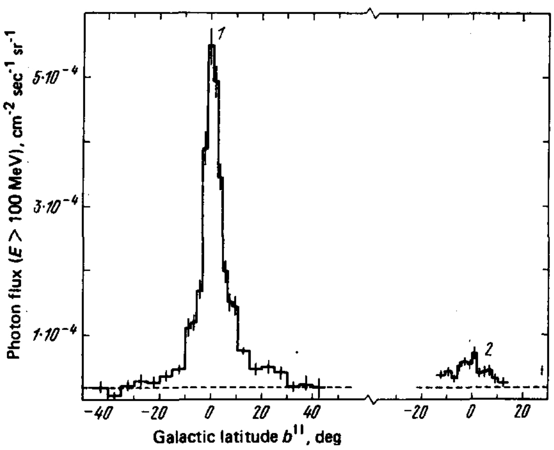

FIG. 3. Latitude distributions of galactic γ radiation with energy greater than 100 MeV from the following regions: 1) Galactic Center ($-30° \leq l^{II} \leq 30°$) and 2) the anticenter ($160° \leq l^{II} \leq 200°$).[2,12]

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[2] On repeated scans of the same portions of the sky, which became possible as the result of continuation of the operation of the telescope, the limiting flux is decreased by a factor $\sqrt{N}$, where N is the number of scans.

moved from us by no more than 3 kpc. The fraction of such "local" γ rays turned out to be ~50% in the flux arriving from the Galactic Center, and almost 100% from the anticenter. These numbers indicate in particular that while at the periphery of the Galaxy there are no large masses of gas or increased fluxes of cosmic rays, on the other hand in the central portions of the Galaxy these components, which are responsible for the γ radiation, are rather large.

The longitude distribution of GGR intensity is shown in Fig. 4. Here we have shown the flux of γ rays with energy greater than 100 MeV, summed over the band of latitudes $-10° \leqslant b^{II} \leqslant 10°$ from various portions of the Milky Way. The dashed line shows the isotropic background.

The region around the Galactic Center in the interval of longitudes from 310° to 40° is distinguished in the intensity of γ radiation with respect to all remaining portions. Five peaks are distinctly observed (maxima at 350°, 330°, 345°, 0°, and 25°), which are apparently due to large-scale features of the galactic structure. An alternative explanation of the peaks as due to discrete γ-ray sources is less probable for the following reasons:

a) All peaks lie on the Galactic Equator ($b^{II} \approx 0°$).

b) The presently known discrete sources of γ rays (see Chapter 3) have appreciably lower intensity than the possible sources responsible for these peaks.

c) The concentration of gas and cosmic rays must be significantly higher in the inner portions of the Galaxy, and this naturally leads to increased γ-ray fluxes.

The arguments presented are not sufficiently strong to reject completely the hypothesis of numerous intense discrete sources of γ rays in the Galaxy whose total intensity produces the observed γ radiation. There are additional arguments which will be discussed below, so that there is a basis for the assumption that the main part of the γ-ray flux arises in the diffuse matter of the Galaxy and features such as the peaks are a manifestation of large-scale structures of interstellar gas, dust, and cosmic rays located at a distance $\lesssim 7$ kpc from the Sun. An alternative hypothesis, however, will also be considered briefly. The peak in the center of the Galaxy ($l^{II} \approx 0$) is approximately twice as broad as the other peaks. It is natural to associate it with an extended galactic nucleus.

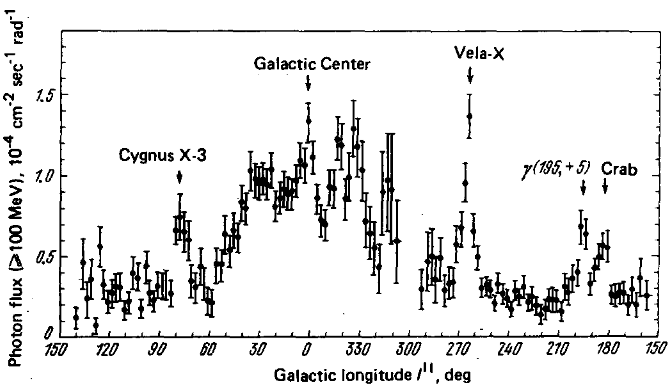


FIG. 4. Distribution of galactic γ radiation with energy $E_\gamma \geqslant 100$ MeV in longitude for the band of latitudes $|b^{II}| \leqslant 10°$.[12]

The nonuniformity of the longitude distribution in other parts of the Milky Way is definitely due to a number of discrete sources: the Crab Nebula, the source Vela-X, etc. (see Chapter 3). Large-scale features of the galactic structure in these locations do not appear so distinctly as in the vicinity of the Galactic Center.

Let us point out a further feature of GGR. It follows from the latitude distributions, which turn out to be asymmetric: for the region of the Galactic Center an excess of the right-hand wing over the left is observed (see curve 1 of Fig. 3), i.e., there is an excess of γ rays in the interval $15° \leqslant b^{II} \leqslant 30°$, and for the region of the anticenter there is an excess in the left wing, in the interval $15° \leqslant b^{II} \leqslant -10°$ (see curve 2 of Fig. 3). A similar asymmetry observed in radio radiation in the distribution of nebulae and dust concentrations in the line of sight has led to the assumption of existence of a local system of stars, gas, and dust in the form of a thin disk of radius 200–300 pc inclined by 15° with respect to the Galactic Plane—the so-called Gould Belt.[13] The fact that GGR reveal the same anomaly serves as an additional indication of the diffuse nature of the γ radiation. A calculation[14] shows that the observed flux of γ rays agrees with the assumption of constancy of the density of cosmic rays over the Gould belt. This is the first, although still qualitative, indication that the density of cosmic rays is constant at a distance 200–300 pc from the Sun.

The diffuse GGR is concentrated mainly in the region of the Galactic Equator. However, as observations of the diffuse radiation at high galactic latitudes carried out in SAS-2 have shown,[15,16] the contribution of galactic radiation remains substantial right up to the poles of the Galaxy.

Fichtel *et al.*[15,16] have determined the intensity of diffuse γ radiation as a function of the galactic latitude b^{II}. The dependence of density on latitude was fitted by the function

$$I(b^{II}) = C_1 + \frac{C_2}{|\sin b^{II}|}, \tag{1}$$

where the constant term corresponded to the contribution of the metagalactic isotropic component and the second term represented the contribution of local regions of the galactic disk. The results of the observations are given in Table I.

Additional confirmation of the appreciable contribution of GGR to the high-latitude diffuse radiation was obtained in Refs. 17 and 18, where a search was carried out for a correlation between the intensity of γ radiation and the quantity of atomic hydrogen, the intensity of nonthermal radio radiation at a frequency $\nu = 150$ MHz, and the location of the H II regions. In these studies it was shown that the contribution of the galactic components to high-latitude diffuse radiation

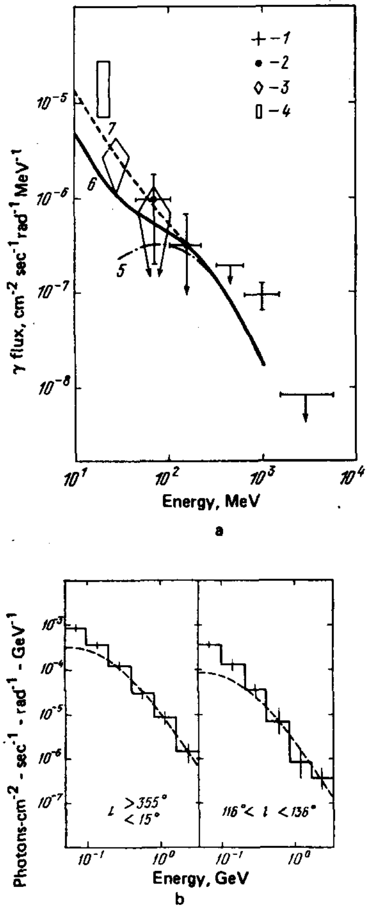
TABLE I.

Region of celestial sphere and energy interval	C_1	C_2
1. $\lvert b^{II}\rvert \geqslant 10°$, $0° \leqslant l^{II} \leqslant 360°$, $E_\gamma \geqslant 100$ MeV	$0.42\cdot10^{-5}$	$1.22\cdot10^{-5}$
2. $\lvert b^{II}\rvert \geqslant 10°$, $0° \leqslant l^{II} \leqslant 360°$, $35 \leqslant E_\gamma \leqslant 100$ MeV	$0.43\cdot10^{-4}$	$0.34\cdot10^{-4}$
3. $\lvert b^{II}\rvert \geqslant 10°$, $60° \leqslant l^{II} \leqslant 300°$, $E_\gamma \geqslant 100$ MeV	$0.52\cdot10^{-5}$	$1.05\cdot10^{-5}$
4. $\lvert b^{II}\rvert \geqslant 10°$, $60° \leqslant l^{II} \leqslant 300°$, $35 \leqslant E_\gamma \leqslant 100$ MeV	$0.47\cdot10^{-7}$	$0.25\cdot10^{-4}$

rises appreciably with increase of the photon energy.

d) Energy spectrum of galactic γ radiation

Spectral measurements of GGR are very important if we are to understand its nature. Different mechanisms of γ-ray production give different energy spectra,[19,20] which differ fundamentally from each other. However, the measurements which have been carried out are insufficient at the present time to make such a distinction. In addition to the small number of the observations, a deficiency is the fact that they have been made with different apparatus, each time in a comparatively narrow energy range (for example, 35–200 MeV in SAS-2). Frequently in view of the poor statistics the spectra are presented in integral form.



a

b

FIG. 5. a) Differential energy spectrum of γ radiation arriving from the vicinity of the Galactic Center[22] ($|b^{II}| \leqslant 10°$, $|l^{II}| \leqslant 30°$; 1—Ref. 11, 2—Refs. 2 and 12, 3—Refs. 9 and 17, 4—Ref. 7. Calculated spectra: 5—pionic flux of γ rays[23], 6—electron bremsstrahlung[23], 7—Compton scattering of electrons[24]); b) differential energy spectrum of γ radiation measured for two regions of the Galaxy (dashed line—spectrum of pionic γ-ray flux[33] normalized at 400 MeV).

Conversion to a differential spectrum requires certain *a priori* assumptions and eventually leads to large errors. Additional information on the spectra, mainly for energies below 30 MeV, has been obtained from balloon observations.[6–11,21a] In Fig. 5a we have shown measurements of GGR in the region of the Galactic Center. For comparison we have shown calculated spectra for various γ-ray production mechanisms. Comparison of the experimental results with the calculated spectra permits the following qualitative conclusions to be drawn:

1. At energies above 100 MeV the pionic γ-ray flux is dominant and consequently the main mechanism of GGR production may be the interaction of cosmic-ray protons and nuclei with interstellar gas.

2. In the range of energies from 10 to 100 MeV an additional γ-ray production mechanism appears, due to bremsstrahlung or inverse Compton scattering of cosmic-ray electrons.

Spectrometric measurements in COS-B have provided more detailed information on the differential energy spectrum of GGR in the range from 50 to 2000 MeV.[21b] In Fig. 5b we have shown spectra measured in two parts of the Milky Way. The shape of the spectra corresponds to the calculated shape for a pionic mechanism in the energy range from 200 to 2000 MeV and departs systematically from the shape in the range from 50 to 200 MeV. This is in general agreement with the assumption made previously that there is a large contribution of bremsstrahlung and Compton radiation at the lower energies.

The spectra measured in six parts of the Milky Way turned out to be identical in shape; this indicates the identity of the γ-ray production processes over the entire Galaxy and is in good agreement with a diffuse nature of GGR.

The substantial difference in the spectra of the isotropic and galactic components of the diffuse γ radiation should be noted. According to Fichtel *et al.*[15] the energy spectrum of the isotropic component of high-latitude radiation can be fitted by the expression

$$F(E_\gamma) = 0.7\cdot10^{-7}\left(\frac{E_\gamma}{100\,\text{MeV}}\right)^{-3.4}\ (\text{photons/cm}^2\text{ - sec - sr - MeV}) \qquad (2)$$

and the spectrum of the galactic component—by the function

$$F(E_\gamma) = 1.1\cdot10^{-7}\left(\frac{E_\gamma}{100\,\text{MeV}}\right)^{-1.6}|\sin b^{II}|^{-1}\ (\text{photons/cm}^2\text{ - sec - sr - MeV}). \qquad (3)$$

This indicates a rapid decrease of the contribution of the isotropic extragalactic component with increase of the photon energy.

According to new data on the spectrum of the isotropic and galactic components of the diffuse radiation, the exponents of the spectra are respectively 2.7(+0.4; −0.3) and 1.5 ± 0.3,[18b] which does not change the general conclusion that there is a decrease in the fraction of the isotropic component with increase of the photon energy.

These conclusions are based on the assumption of a diffuse nature of GGR. Numerical agreement of the measured and calculated fluxes confirms this assumption. Consequently GGR can serve as a means of study of the concentration, composition, and spatial distribution of gas and cosmic rays in the Galaxy.

e) Interpretation of diffuse GGR

Let us therefore assume that the electromagnetic radiation in the γ-ray range is the product of interaction of high-energy particles with the interstellar medium. Photons with energy exceeding $E_\gamma \sim 10$ MeV can arise in such processes as:

1) decay of π^0 mesons arising in interaction of the nuclear component of cosmic rays with interstellar gas;

2) bremsstrahlung of electrons which collide with particles of the interstellar gas,

3) inverse Compton scattering of photons of the relict and stellar radiation by ultrarelativistic electrons;

4) Synchrotron radiation of electrons of very high energy ($E_\gamma \gtrsim 10^{15}$ eV).

The luminosity of a unit volume of the interstellar medium is determined by the characteristics of the interaction, the intensity and energy spectrum of the nuclear and electronic components of cosmic rays, and the parameters of the interstellar medium—the concentration of gas and the energy spectrum of the background electromagnetic radiation.

Let us consider the basic mechanisms of γ-ray production in the interstellar medium.

1) *The neutral-pion mechanism.* Decay of π^0 mesons arising as the result of strong interactions of cosmic rays with the interstellar gas is the main mechanism of γ-ray production for energies $E_\gamma \gtrsim 50-100$ MeV in the interstellar medium. The luminosity of a unit volume of the interstellar medium in this case is determined by the expression

$$q(E_\gamma) = Kn_{\mathrm{H}} \int\limits_{E_\gamma + (m_\pi^2 c^4/4E_\gamma)}^{\infty} dE' \frac{2E_\gamma}{\sqrt{E'^2 - m_\pi^2 c^4}} \int\limits_{E_{\mathrm{th}}^*}^{\infty} dE_p j(E_p) \frac{d\sigma(E_p, E')}{dE'}, \tag{4}$$

where $K = 1.64$ is a coefficient taking into account the influence of the chemical composition of the interstellar gas and the cosmic rays, n_{H} is the concentration of hydrogen nuclei in the interstellar medium, $j(E_p)$ is the differential energy spectrum of the proton component of cosmic rays, E_{th}^*(MeV) is the threshold energy for π^0-meson production, E_γ, E_p, and E' are the energies of the photons, protons, and π^0 mesons, and $d\sigma(E_p, E')/dE'$ is the differential cross section for production of π^0 mesons.

Calculation of the function $q(E_\gamma)$ has been carried out by many authors (see for example Refs. 25–29); the discrepancies in the results of the calculations have been as large as several tens of percent. This is explained first of all by the inaccurate approximation of the differential cross section for π^0-meson production. In the proton-energy region from 2 to 10 GeV most important for production of photons with energy $E_\gamma \gtrsim 100$ MeV, the cosmic-ray spectrum in the vicinity of the solar system is known comparatively well and can be fitted by the expression[30-32]:

$$j(E_p) = \begin{cases} 7\cdot 10^3 E^{-2.5}\,(m^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}) & (3 \leqslant E_p \leqslant 70\,\mathrm{GeV}, \\ 2.0\cdot 10^{-4} E^{-2.75}\,(m^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}) & (E \geqslant 70\,\mathrm{GeV}. \end{cases} \tag{5}$$

An important step in the direction of improving the calculations of the function $q(E_\gamma)$ was made by Badwar and Stephens.[33] These authors used an empirical expression for the cross section

$$\frac{d\sigma(E_p, E')}{dE'} = 2\pi \int d\vartheta p_\perp E' \frac{d^3\sigma}{dp'}, \tag{6}$$

where the invariant cross section $E'd^3\sigma/d\mathrm{p}'$ was approximated by the function

$$E' \frac{d^3\sigma}{dp'} = \frac{A}{1.0 + (4m_p^2 c^4/s)} (1-\tilde{x})^q \exp\left[-Bp_\perp \left(1.0 + \frac{4m_p^2 c^4}{s}\right)^{-1}\right]; \tag{7}$$

here $p_\perp$ is the transverse momentum of the meson, ϑ is the angle of emission of the meson, s is the square of the total energy in the center-of-mass system,

$$\tilde{x}^2 = x_\parallel + \frac{4}{s} c^2 p_\perp^2 + m_\pi^2 c^4),$$

$$q = \frac{C_1 + C_2 p_\perp + C_3 p_\perp^2}{\sqrt{1.0 + (4m_p^2 c^4/s)}},$$

and $x_\parallel$ is the ratio of the parallel component of the meson momentum to the maximum possible momentum in the center-of-mass system. The values of the constants are $A = 135$ mb-sec^3/GeV^2, $B = 5.45$ sec/GeV, $C_1 = 6.18$, $C_2 = 4.0$ sec/GeV, and $C_3 = 1.25$ (sec/GeV)^2. The expression (7) satisfactorily describes the measured differential cross sections for production of pions in accelerators. The integral spectrum is shown in Fig. 6, and the results of numerical calculation of the function $q(E_\gamma)$ are given in Fig. 7.

The spectrum of γ rays of pionic origin is characterized by a broad maximum in the energy region $E_\gamma \approx 70$ MeV. In the high-energy region the photon spectrum becomes a power spectrum:

$$\frac{q(E_\gamma)}{n_{\mathrm{H}}} = 2.52\cdot 10^{-27} E^{-2.75}\ (\text{photons/sec - sr - GeV}) \tag{8}$$

for $E_\gamma \gtrsim 20$ GeV.

2) *The bremsstrahlung mechanism.* The luminosity of a unit volume of the interstellar medium corre-

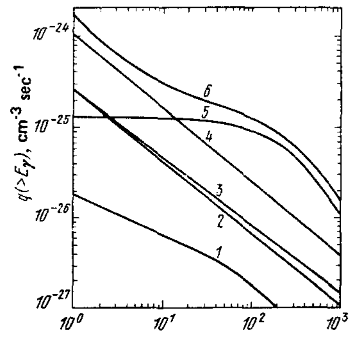


FIG. 6. Integral luminosity of a unit volume of the interstellar medium in the vicinity of the solar system. The concentration of interstellar gas is $n_H = 1$ cm^{-3}; the energy density of the stellar background radiation is $w = 0.44$ ev/cm^3. 1—Compton effect on optical photons, 2—Compton effect on relict radiation, 3—total Compton effect, 4—bremsstrahlung, 5—decay of π^0 mesons, 6—the sum of all processes.

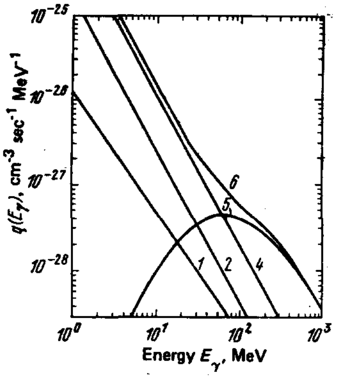


FIG. 7. Differential luminosity of a unit volume of the interstellar medium. The parameters of the medium and the designations are the same as in Fig. 6.

sponding to the bremsstrahlung of relativistic electrons is determined by the expression

$$q_B(E_\gamma)=K_1 n_{\mathrm{H}} \int\limits_{E_\gamma}^{\infty} dE_e\, j_e(E_e)\, d\sigma(E_e, E_\gamma)\frac{1}{dE_\gamma}, \tag{9}$$

where $d\sigma(E_e, E_\gamma)/dE_\gamma$ is the Bethe-Heitler differential cross section and $K_1=1.3$ is a coefficient taking into account the chemical composition of the interstellar gas. In contrast to the pionic mechanism, in this case the principal uncertainty in calculation of the function $q_B(E_\gamma)$ involves the value of the differential spectrum of the electronic component in interstellar space $j_e(E_e)$; the cross section for this process is known with high accuracy. A detailed analysis of the γ-ray production function in bremsstrahlung in the interstellar medium has been carried out by Shukla and Cesarsky,[34] who showed that the uncertainty of the function $q_B(E_\gamma)$ in the range of energies from 10 to 100 MeV can exceed an order of magnitude. The results of the calculations are shown in Fig. 7, together with the function $q(E_\gamma)$ for the pionic mechanism. It can be seen from Fig. 7 that the bremsstrahlung mechanism should be dominant in the energy region $E_\gamma \lesssim 50$ MeV; the exact boundary of the transition from one mechanism to the other depends on the intensity of the electronic component. Determination of the spectrum of GGR in the energy region $E_\gamma = 10-100$ MeV in the direction of the anticenter will permit determination of the flux of the electronic component at low energies in the vicinity of the solar system.

In the vicinity of the solar system the contribution of the inverse Compton effect to the luminosity of a unit volume of the interstellar medium in the γ-ray region is insignificant (less than 10%). This production mechanism may become the principal one in those regions of the Galaxy where the energy density of the background radiation of the stars is much greater than in the vicinity of the solar system (for example, at the Galactic Center). Nevertheless the calculations show that the contribution of the inverse Compton effect to the observed intensity of diffuse GGR can be neglected even in the direction of the Galactic Center.[35] The contribution of the synchrotron mechanism is less by several orders of magnitude than that of the Compton mechanism.

Thus, the formation of the diffuse GGR is determined by two principal mechanisms—the decay of π^0 mesons and the bremsstrahlung of electrons.

A general idea of the distribution of GGR sources, regardless of their nature, can be obtained from analysis of the GGR intensity distribution as a function of galactic longitude (see Fig. 4). The relation between the distribution of luminosity of a unit volume in γ rays over the Galaxy $q(\mathbf{r})$ and the GGR intensity distribution as a function of longitude $I(l^{\mathrm{II}})$ has been considered in several studies.[24,36,37] The results, although they differ somewhat from each other, indicate a common feature—increase of the volume luminosity in γ rays in a ring-shaped region located at a distance of about 5 kpc from the Galactic Center. In Fig. 8 we have shown the volume luminosity as a function of the distance to the Galactic Center as calculated by Stecker.[37]

This fact cannot be called unexpected. Similar properties are possessed not only by the distribution of volume luminosity of the interstellar medium in the γ-ray range, but also by the distribution of volume luminosity in the lines at 2.6 mm (the transition $J=1 \to J=0$ of the CO molecule) and H 166α, and also by the distribution of supernova remnants and giant H II regions (Fig. 9).[38] A maximum in the region 4–8 kpc is observed in the distribution of the concentration of molecular hydrogen (Fig. 10).[39]

The coincident maxima in the distribution of the diverse components of our Galaxy are due to a single cause—generation of a strong shock wave in the interstellar gas under the influence of a gravitational density wave.[40,41] Compression of the gas behind the front of a strong shock wave can serve as the trigger mechanism for gravitational collapse of interstellar clouds and acceleration of the process of star production, which in turn leads to an increase in the number of astrophysical objects related to the stellar population of type II, giant H II regions, supernova remnants, and pulsars. The nature of the shock wave in the interstellar gas initiated by a gravitational density wave will depend on the relation between the velocity of sound a in the interstellar gas and the component velocity of the gas $w_\perp$ perpendicular to the spiral arm of the Galaxy. In the outer region of the Galaxy at distances from its center greater than 8–10 kpc, we have

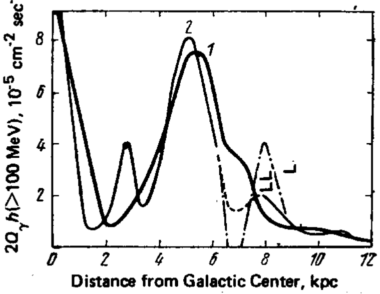


FIG. 8. Radial distributions of volume luminosity.[37] Curve 1 corresponds to the longitude region $0 \leqslant l^{\mathrm{II}} \leqslant 180°$. Curve 2 corresponds to the region $180° \leqslant l^{\mathrm{II}} \leqslant 360°$. L—constructed from the average values of the experimental points. LL—from the lower limits.

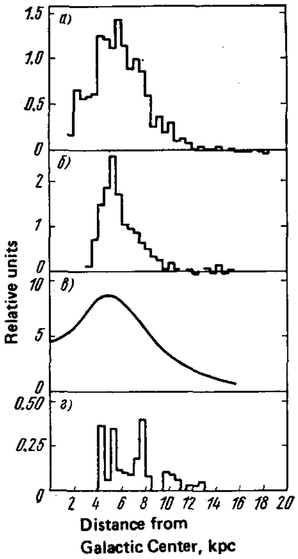


FIG. 9. Distribution of galactic components over the galactic disk: volume luminosity in the CO lines (a), H 166*α* (b), concentration of supernova remnants (c), and of giant HII regions (d).

$w_\perp \leq a$ and the shock wave is weak. In the inner region $w_\perp > a$ and in this case the shock wave provides rather strong compression of the interstellar gas, which leads to acceleration of star production. The characteristics of the density wave in our Galaxy are given in Fig. 11.[41]

The insufficient statistical reliability of these observations, the poor angular resolution of existing gamma telescopes, and the definite arbitrariness in the method of analysis of the longitude distribution of the diffuse GGR intensity lead to the result that the calculated distributions of the volume luminosity of γ rays in the interstellar medium are not yet unique. Detailed investigation of the structure of the Galaxy by the methods of γ astronomy will require use of more sensitive telescopes with better angular resolution and use of more reliable data on the distribution of the various components of the interstellar medium. Nevertheless the interpretation of the observed diffuse GGR in terms of various models of the structure of the Galaxy continues to attract the attention of astrophysicists. Recently a number of theoretical papers have been published which explain more or less satisfactorily the distribution of intensity of the diffuse GGR in galactic longitude, but up to this time a final choice between various models cannot be made.

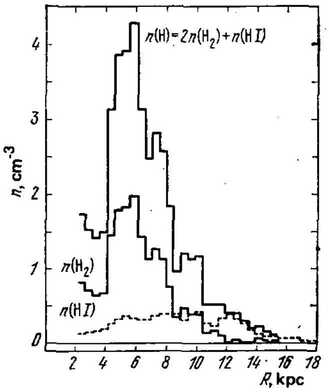


FIG. 10. Distribution of concentration of atomic and molecular hydrogen over the galactic disk.

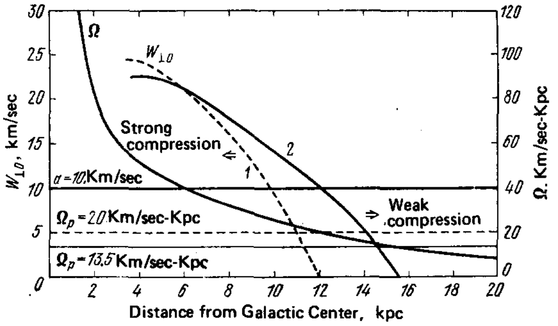


FIG. 11. Characteristics of density waves in the Galaxy. The curves of $w_\perp$ as a function of the distance to the center of the Galaxy correspond to two values of rotational angular velocity of the wave structure Ω: $\Omega_p = 20$ km/sec-kpc (1), $\Omega_p = 13.5$ km/sec-kpc (2).

All of the proposed models are based on a single assumption regarding the nature of the diffuse GGR—the hypothesis of production of GGR in interaction of cosmic rays with the interstellar gas. In this case the intensity of the diffuse GGR is determined by the relation

$$F_\gamma(E_\gamma, \Omega) = \frac{1}{4\pi}\int_{(L)} dl\, n(\mathbf{r})\, q(E_\gamma)\frac{F_{\mathrm{cr}}(\mathbf{r})}{F_{\mathrm{cr}}(0)}, \qquad (10)$$

where $n(\mathbf{r})$ is the concentration of interstellar gas, $q(E_\gamma)$ is the differential (or integral) luminosity per hydrogen atom in the vicinity of the solar system, and $F_{\mathrm{cr}}(\mathbf{r})/F_{\mathrm{cr}}(0)$ is the ratio of the intensity of cosmic rays at the point of production to the intensity in the vicinity of the solar system.

f) The interstellar gas

Information on the distribution of the interstellar gas concentration over the Galaxy can be obtained from radio-astronomy observations.[38] Neutral atomic hydrogen, which until recently was assumed to be the main component of the interstellar gas, is observed on the basis of the well known line with wavelength $\lambda = 21$ cm corresponding to the transition between hyperfine-structure levels. Radio-astronomy observations permit a quasi-three-dimensional image of the intensity of radiation at the $\lambda = 21$ cm line to be obtained as a function of the coordinates in the celestial sphere and also of the radial velocity of the radiating object. Analysis of the results of the observations will permit determination of the actual three-dimensional distribution of atomic-hydrogen concentration over the Galaxy.

Several years ago observations of interstellar absorption in the ultraviolet region showed that there is present in interstellar space not only atomic hydrogen, but also molecular hydrogen.[41,42] In open interstellar space the concentration of molecular hydrogen is small as the result of destruction of molecules in the photodissociation process,[43] but in dense gas and dust clouds, the inner regions of which are screened from the ultraviolet radiation which destroys the molecules, molecular hydrogen becomes the main component of the interstellar medium.

Unfortunately no direct method of determining the concentration of molecular hydrogen in the remote regions of the Galaxy exists at this time and its concentration must be estimated indirectly—from observation of the radiation of CO in the 2.6-mm line. The intensity of radiation in the 2.6-mm line depends on the concentration of H_2, since the collisions of the CO molecules with H_2 molecules are the main mechanism of excitation of the rotational levels of the carbon monoxide molecule.

The distribution of molecular hydrogen concentration in the Galaxy is calculated on the basis of observations of the intensity distribution of the 2.6 mm line as a function of galactic latitude and longitude, and also on the basis of the radial velocity. In comparison of the distributions of atomic and molecular hydrogen in the Galaxy (see Fig. 10) one is stuck with the great difference between them: while the atomic hydrogen is distributed more or less uniformly, the molecular hydrogen is concentrated in a ring-shaped region at distances 5–8 kpc from the Galactic Center. As was noted earlier, this is a consequence of the passage of a strong shock wave which compressed the interstellar clouds.

The distribution of ionized hydrogen is determined from observations of the recombination lines.[38,44] The concentration of ionized hydrogen is substantially less than the concentration of neutral hydrogen, and need not be taken into account in calculation of the production of diffuse GGR.

g) Cosmic rays in the galaxy

In the basic expression (10) for the intensity of diffuse GGR there is still one parameter whose determination is extremely important for the theory of the origin and propagation of cosmic rays in the Galaxy—the ratio of the concentration of cosmic rays in the remote regions of the Galaxy to their concentration in the vicinity of the solar system. Gamma-astronomy observations are a unique method of remote measurement of the intensity of cosmic rays and they have already led to interesting results.

In particular, one can now consider that the distribution of cosmic rays in the Galaxy is nonuniform. In the outer part of the Galaxy at distances of more than 10 kpc from its center, the intensity of cosmic rays should be appreciably less than in the vicinity of the solar system (in the opposite case the intensity of GGR in the direction of the anticenter would be significantly greater than that observed[45,46]). This fact is a serious argument against the metagalactic origin of cosmic rays, in which one would expect a uniform distribution of the intensity over the Galaxy.

Interpretation of the observations of diffuse GGR indicates apparently also a nonuniform distribution of cosmic-ray intensity in the inner regions of the Galaxy. We can suppose, as is shown by Fig. 12 (Ref. 24), that the distribution of cosmic-ray intensity over the Galaxy corresponds to the distribution of supernova remnants.[47] Calculations carried out with this distribution are in good agreement with the observations of GGR. Nevertheless final conclusions regarding the distribution of cosmic rays in the inner regions of the Galaxy cannot yet be drawn. The incompleteness of the observational data and the uncertainty in the initial premises of the interpretation lead to the result that satisfactory agreement with the observations is achieved with various models of the distribution of cosmic rays in the inner region of the Galaxy—both with the assumption of proportionality of the cosmic-ray intensity to the density of the interstellar gas[48-50] and also even with a constant intensity of cosmic rays in the inner region of the Galaxy.[51] A final solution of the problem of the cosmic-ray distribution in the inner region of the Galaxy can be obtained only when GGR observations of higher quality are made and they are interpreted in detail with allowance for the various features of the galactic structure and the process of GGR production in the interstellar medium.

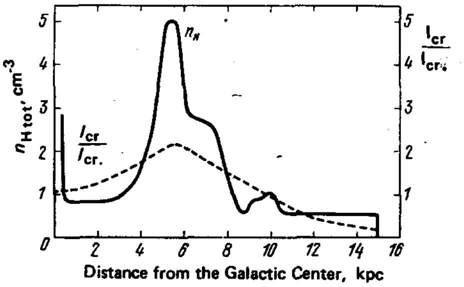


FIG. 12. Distribution of cosmic-ray intensity and concentration of interstellar hydrogen over the Galaxy.

In particular, the interpretation of GGR in the region of low galactic longitudes ($-60° \leq l^{II} \leq 60°$) may be complicated by the fact that an appreciable part of the observed diffuse background is due to the contribution of unresolved discrete sources (for example, pulsars[52,53]). In the outer region of the Galaxy the contribution of discrete sources may reach 30% of the total intensity.[46]

Compression of interstellar clouds can be accompanied by an enhancement of the magnetic field and a reduction of the cosmic-ray intensity in the inner regions of dense interstellar clouds.[54] This leads to a reduction of the efficiency of GGR production in dense clouds.[46,55]

GGR observations permit information to be obtained on the distribution of cosmic rays not only in the disk, where the gaseous component of the interstellar medium is concentrated, but also outside the disk in the so-called galactic halo. The principal information on the cosmic-ray halo has been obtained from observations of synchrotron radio radiation of the electron component of cosmic rays. Analysis of the propagation of electrons with allowance for their energy loss has shown that the transverse dimensions of the halo of relativistic electrons are limited,[56] but no limitations on the thickness of the halo of the nuclear component have been found up to this time.[57,58] Stecker and Jones[59] showed that observations of the latitude distribution of GGR intensity impose limitations on the thickness of the halo of the nuclear component of cosmic rays: $h \lesssim 3$ kpc.

3) DISCRETE SOURCES OF γ RAYS

Discrete sources (DS) of γ rays in the Galaxy are observed in a background of diffuse radiation. Where the diffuse flux is comparatively small they are distinguished rather clearly and yield a number of appreciable peaks (denoted in Fig. 4 by arrows). In regions of increased GGR intensity they are submerged in the diffuse flux. In addition to spatial separation of discrete sources, which as a consequence of the inadequate angular resolution of existing γ telescopes can be carried out only for intense sources, they can be identified also on the basis of their energy and time characteristics. It is the latter which permit us at the present time to speak with a high degree of confidence of discrete γ sources and to associate them with definite astrophysical objects.

a) The Crab Nebula and pulsar PSR 0531 + 21

The Crab Nebula and the pulsar at its center—the remnant of Supernova 1054—are one of the best known and best studied sources of nonthermal radiation in the Galaxy. The radiation of this source has been observed over a wide range of wavelengths, including γ rays from the soft region ($E_\gamma = 0.1-1$ MeV) to the ultra hard region ($E_\gamma = 10^{11}-10^{13}$ eV). In the x-ray region the energy spectra of the nebula and the pulsar have a power law[60]: $F(E_\gamma) = 21.8 E_\gamma^{-1.29}$ (keV/cm^2-sec-keV) for the total flux and $F(E_\gamma) = 0.7\ E_\gamma^{-0.9}$ (keV/cm^2-sec-keV) for the pulsating flux.

The spectrum of the pulsar is more energetic, and therefore the fraction of pulsating radiation constantly increases as the γ-ray energy increases. This is confirmed also by the results of the recent observations in SAS-2 and COS-B.[61,62] In the observations in COS-B the constant component was not observed at all; the lower limit of the fraction of pulsating radiation, depending on the energy, amounted to from 72 to 78% (at the 2σ level). The observations in SAS-2 indicate the presence of a constant component in the energy region from 35 to 100 MeV; in this case the fraction of pulsating component amounts to about 50%.

A summary of the results of observations of pulsar PSR 0531+21 in SAS-2 and COS-B are given in Table II.

The pulse of γ radiation is essentially no different in shape from the pulses in the radio, optical, and x-ray regions (Fig. 13), although some insignificant changes are observed (increase of the sub-pulse, and delay of the γ pulse relative to the radio pulse by 1–2 msec).

The question of the existence of γ radiation of the Crab Nebula in the energy range $E_\gamma \gtrsim 40-100$ MeV remains open. If the SAS-2 results are confirmed, this will mean that in the Crab Nebula there are present electrons with energy $E_e \gtrsim 10^{15}$ eV.

It is not excluded that the γ radiation of pulsar PSR 0531+21 is subject to time variations—in various energy intervals changes have been observed in the intensity of the pulsating radiation.[63-65] An increase in the intensity occurred after the jump in the period of the pulsar,[63,64] which arose as a result of a spontaneous change of the angular rotational velocity of the neutron star during its internal rearrangement. It is interesting to note that in all cases the total loss of energy of the neutron star, determined by the change in velocity of rotation of the pulsar, increased by only 10–15% after the jump of the period, while the intensity of the γ radiation increased by 2–3 times. In this case the jump in period serves primarily as a release device for the γ-ray production processes.

TABLE II. Results of observations of pulsars in the Crab Nebula and in Vela-X.

	PSR 0531+21	PSR 0833-45
	SAS-2	
$E \geqslant 35$ MeV	8.2 ± 1.5	29.5 ± 2.4
$E \geqslant 100$ MeV	2.9 ± 0.5	12.0 ± 1.2
	COS-B	
$E \geqslant 50$ MeV	5.9 ± 0.8	15.6 ± 0.8
$E \geqslant 200$ MeV	1.3 ± 0.3	5.3 ± 0.4

*The intensity of the radiation is expressed in units of 10^{-6} photons/cm^2-sec.

b) The nebula Vela-X and pulsar PSR 0833-45

This source also is a supernova remnant, but its age is somewhat greater than for the Crab Nebula—about 10^4 years. The preliminary results of the SAS-2 observations which show the existence of a constant component[66] have not been confirmed; the latest data of SAS-2 and COS-B, given in Table II, indicate that practically all of the radiation of the source pulsates with a period 89 msec coincident with the period

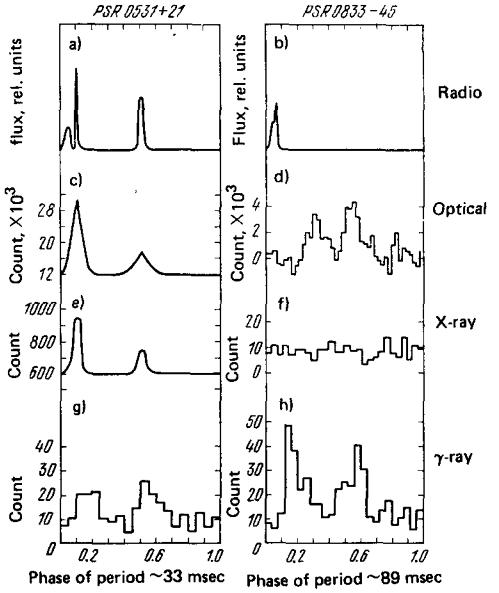


FIG. 13. Shapes of pulses of radiation from the pulsars of the Crab Nebula and Vela-X in various regions. Radio region: a) 430 MHz,[129] b) 8.4 Hz.[130] Optical region: c) from Ref. 131, d) from Ref. 132. X-ray region: e) 0.5—10 keV,[133] f) 0.1—1.5 keV.[134] Gamma-ray region: g and h) $E_\gamma \geqslant 35$ MeV.[61]

of the radio pulsar PSR 0833-45.[61]

In this case, in contrast to the pulsar in the Crab Nebula, the shape of the γ pulse differs substantially from that of the pulse in the radio and optical regions (see Fig. 13). If we compare the pulsars PSR 0531+21 and PSR 0833-45, we are struck with a marked dissimilarity in all regions except the γ-ray region. In both cases the shape of the pulse is double, the main pulse is narrow, the intermediate pulse somewhat broader, and the time interval between the pulses is about 0.4 of the period. This similarity is undoubtedly not accidental. It indicates that the pulsar phenomenon is determined primarily by high-energy processes associated with generation of γ rays, and not secondary processes leading to generation of radio, optical, and even x-ray radiation. This is also indicated by the energetics of pulsars: The luminosity of pulsars in the γ-ray region is several orders of magnitude higher than that in the other wavelength regions.

In addition to the obvious similarity in the γ-ray properties of pulsars PSR 0833-45 and PSR 0531+21, certain differences are observed. Thus, while the spectrum of the pulsar in the Crab Nebula is strictly power-law, the spectrum of the pulsar PSR 0833-45 has a more complicated shape.[61] The cause of this difference remains unclear.

The luminosity of pulsar PSR 0833-45 in the γ-ray region is somewhat less than for the pulsar PSR 0531+21, which is undoubtedly explained by the difference in the age of the pulsars (10^4 and 10^3 years, respectively). Nevertheless the γ-ray flux falls off with age much more slowly than the fluxes in the other regions, so that the fraction of the energy release of the pulsar going into γ radiation apparently increases with the passage of time. This conclusion has served as the starting point for the search for γ radiation from other pulsars, including old ones.

c) Gamma pulsars

An extensive search for γ radiation from pulsars was first carried out on the basis of the SAS-2 data.[67] Among 73 pulsars for which there were correlated observations in the radio and γ regions, two additional γ pulsars were observed—PSR 1747-46 and PSR 1818-04. Their parameters are given in Table III. It should be noted that the search is hindered by the fact that the insufficient accuracy of measurement of the derivatives of the period of radio pulsars and the possibility of jumps in the periods make it difficult to predict accurately the phase of pulsars, which is necessary in a correlation analysis of observational data in the γ-ray range. Therefore the results of this study[67] must be considered primarily as a lower limit of the number of γ pulsars among radio pulsars.

A search for γ pulsars was carried out also on the basis of the results obtained in COS-B.[68] In this case correlated observations in the radio and γ ranges existed for 88 pulsars which were divided into two groups, depending on the accuracy of prediction of the phase of the pulsars. In the first group there were 55 pulsars for which the accuracy of phase prediction was sufficient for a direct correlation analysis of the time distribution of the γ rays. No γ rays were observed in any of the pulsars of this group, including the proposed γ pulsar PSR 1818-04. The accuracy in prediction of the phase of the pulsars of the second group was insufficient for direct correlation, and the analysis of the observational data was carried out by the method of searching in a narrow region of values of the period P and its derivative $\dot{P}$. In this group two candidates for γ pulsars were found: PSR 1742-30 and PSR 1822-09. Their parameters are also given in Table III.

We can see certain coincident features in the shapes of the pulses of these and the previously discussed pulsars, but as a whole they differ substantially. The

TABLE III.

Source	Type	Distance, kpc	Distance P, sec	Age $\tau = P/2p$, years	γ radiation			Ratio
					Energy E_γ, MeV	Flux $F_\gamma(>E_\gamma)$, cm^{-2}sec^{-1}	Luminosity* $L_\gamma(>E_\gamma)$, ergs/sec	$\frac{F_{\text{rad}}(400\text{ mHz})}{F_\gamma>(100\text{ MeV})}$
Crab Nebula	Shell	2.0		10^3	35	$(6\pm3)\cdot10^{-6}$	$2.5\cdot10^{35}$	
PSR 0531+21	Pulsar	2.0	0.033	10^3	35	$(8\pm1.5)\cdot10^{-6}$	$3.5\cdot10^{34}$	$10^{8.4}$
Vela-X	Shell	0.5	—	10^4	35	$(4.5\pm2.1)\cdot10^{-6}$	10^{34}	
PSR 0833-45	Pulsar	0.5	0.089	10^4	35	$(29.5\pm2.4)\cdot10^{-6}$	$7.5\cdot10^{33}$	$10^{8.8}$
PSR 1818-04	»	3.2	0.598	1.5 10^6	35	$(2.0\pm0.5)\cdot10^{-6}$	$2\cdot10^{34}$	$10^{8.1}$
PSR 1747-46	»	0.74	0.742	1.7 10^5	35	$(2.4\pm0.7)\cdot10^{-6}$	$1.5\cdot10^{33}$	$10^{8.0}$
(195+5)	» (?)		59.0074	?	100	$(4.3\pm0.9)\cdot10^{-6}$		$< 10^{9.5}$
Cygnus X-3	Pulsar in binary system (?)	10	$1.728\cdot10^4$	?	40 10^6	$(6.5\pm1.7)\cdot10^{-5}$ $3\cdot10^{-11}$	$7.5\cdot10^{36}$ $1.0\cdot10^{35}$	
Galactic Center	Galactic nucleus	10			100	$5\cdot10^{-6}$	$2.1\cdot10^{37}$	
PSR 1742-30	Pulsar	2.9	0.367	$5\cdot10^5$				
PSR 1822-09	»	0.65	0.769	$2\cdot10^5$				

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*For pulsars the angle of the radiaton is taken as 1 sr.

most general characteristic which unites the entire group of four γ pulsars is the ratio of the radio and γ fluxes. This quantity, as can be seen from the table, varies within the limits $10^{8.0}$–$10^{8.8}$ and can serve as a criterion in the search for new γ pulsars, and also in the search for radio pulsars from regions of excess γ radiation.

The detection of γ radiation from the pulsars PSR 0531+21, PSR 0833-45, PSR 1747-46, and PSR 1818-04 initiated a new direction in study of the dynamics of the magnetospheres of pulsars. While the discovery of γ radiation of the two pulsars having a high rotational velocity was not unexpected, the observation of γ radiation of the slowly rotating pulsars has placed astrophysicists in a difficult position. These pulsars emit in the γ-ray range a significant part of the rotational energy liberated in slowing down of the pulsar.

To explain the intense γ radiation of pulsars, use has been made of the ideas of Sturrock[69] on the radiation of relativistic particles moving along curves lines of force, absorption of photons in a strong magnetic field with production of electron-positron pairs, and development of electron-positron showers. These ideas have been used for the interpretation of energetic pulsar radiation in Refs. 70–74. The most detailed analysis of models of pulsar γ-ray production has been made by Ozernoĭ and Usov.[72] They obtained satisfactory agreement of theoretical results and the observed characteristics of γ pulsars. The γ radiation of pulsars is generated at a distance 5–10 radii of the neutron star from its surface; the γ radiation does not leave the deeper regions of the magnetosphere, since it is absorbed in the magnetic field with production of electron-positron pairs. The absence of observed γ radiation in a number of radio pulsars is explained by these authors[72] as due to the different orientations of the directivity diagrams of the pulsars in the radio and γ ranges.

Buccheri *et al.*[74b] used the pulsar-polar-cap model of Ruderman and Sutherland[74c] to obtain empirical expressions for the efficiency η_γ of conversion of the energy $\dot{E}$ dissipated in slowing down of the rotation of the neutron star into energy of γ radiation and for the flux of γ radiation F of pulsars:

$$\eta_\gamma \backsim \frac{P}{\dot{P}} \approx \tau, \tag{11}$$

$$\frac{F}{F_{\text{Cr}}} = \eta_\gamma \frac{4\pi I\dot{P}}{P^3 D^2}\left(\frac{D^2}{L_\gamma}\right)_{\text{Cr}}, \tag{12}$$

where $\mathring{E} = 4\pi I\dot{P}/P^3$, I is the moment of inertia of the neutron star, P and $\dot{P}$ are the pulsar period and its derivative with respect to time, τ is the age of the pulsar, and D is the distance to the pulsar; the subscript Cr indicates quantities associated with the pulsar PSR 0531+21 in the Crab Nebula.

In Table IV we have given estimates of the fluxes from the 15 most promising pulsars with a flux exceeding 5% of the flux of the pulsar PSR 0531+21. The calculated fluxes are in good agreement with the measured fluxes for the pulsars PSR 0833, PSR 1747, PSR 0822, and the pulsar recently observed in COS-B PSR 0740.[21b] On the other hand, the expected fluxes of γ rays from the pulsars PSR 1818 and PSR 1742 are much less than the observed fluxes (we note that the γ radiation of PSR 1818 observed in SAS-2 was not confirmed in COS-B).

TABLE IV.

PSR	P, sec	τ, years	F/F_{Cr} Estimate	F/F_{Cr} Observ-ations
0833—45	0.089236	$1.13\cdot10^4$	3.3	3.3
0531+21	0.033098	$1.24\cdot10^3$	1.0	1.0
0950+0.8	0.253065	$1.73\cdot10^7$	<1.0	
1929+10	0.226517	$3.\ 0\cdot10^6$	<0.8	
1642—03	0.387689	$3.45\cdot10^6$	<0.8	
1706—16	0.653050	$1.62\cdot10^6$	<0.7	
0355+54	0.156380	$5.64\cdot10^5$	0.4	
1747—46	0.742352	$1.68\cdot10^5$	0.3	0.3
0740—28	0.166752	$1.57\cdot10^5$	0.3	
1822—09	0.768950	$2.35\cdot10^5$	0.2	0.3
0611+22	0.334919	$8.88\cdot10^4$	0.15	
1915+13	0.194626	$4.28\cdot10^5$	0.06	
1133+16	1.187911	$5.04\cdot10^6$	0.05	
1451—68	0.263377	$4.35\cdot10^7$	0.05	
2223+65	0.682533	$1.14\cdot10^6$	0.05	

d) The discrete source CG (195 + 5)

Excess fluxes of γ rays with an angular width corresponding to the radiation of discrete sources were recorded by SAS-2 (Refs. 2 and 14) and COS-B (Ref. 4) from the region bounded by the galactic coordinates $b^{\text{II}} = +4.9 \pm 0.2°$, $l^{\text{II}} = 195 \pm 2.2°$. Although the flux of γ rays from the source is no less than from the Crab Nebula, it has up to the present time not been identified with any astrophysical object. Attempts at identification with supernova remnants[14] and also with a dwarf satellite galaxy[75] were not warranted after refinement of the source location. In the latter case it was necessary to assume an extraordinarily large flux of cosmic rays in the satellite galaxy, 10^2–10^3 times greater than in the vicinity of the Sun.

An interesting feature of the source CG (195+5) is the 59-second periodicity, which was observed both in SAS-2 (Ref. 76) and in COS-B.[77] The accurate values of the period P and its derivative $\mathring{P}$ are (at the time *JD* = 2442656.5)

$$P = 59.19687 \text{ sec}, \quad \dot{P} = 1.39\cdot10^{-9}\ \text{sec}^{-1}.$$

The fraction of pulsating γ radiation is 75 ± 25%. The values of the period and its derivative are quite unusual for typical radio pulsars.

e) Cygnus X-3

The x-ray source Cygnus X-3, which was discovered in 1966 (Ref. 78) and did not attract special attention until the fall of 1972, has become at the present time one of the best known astrophysical objects. On 2 September 1972 Canadian radioastronomers unexpectedly observed a very intense burst of radio radiation associated with Cygnus X-3.[79] This discovery led to the development of an extensive international program of investigation of Cygnus X-3 over a wide range (from radio waves to γ rays), which has given a number of astonishing results. First, the x rays of Cygnus X-3 turned out to be periodic, and the period value ($P = 4.8$ hours) is quite unusual for x-ray sources: too small for orbital motion and too large for rotation of a compact object.[80,81] Second, Cygnus X-3 was identified with a source of infrared radiation whose intensity varied with the same period.[82] Finally, γ radiation was observed from Cygnus X-3 in the region $E_\gamma \geqslant 40$ MeV (Refs. 83–85) and $E_\gamma \sim 10^{12}$ eV.[86,87] The results of observations in the γ-ray region also indicate periodic intensity variation with a period 4.8 hours.

In Fig. 14 we have shown the distribution during the 4.8-hour period of the γ-ray fluxes in the two energy intervals $E_\gamma \geqslant 4\times 10^7$ eV and $E_\gamma \geqslant 10^{12}$ eV. The main part of the flux is concentrated in a narrow radiation pulse of duration less than an hour. This nature of the radiation may possibly have been the reason that the γ radiation of Cygnus X-3 was not observed in a number of studies.[88,89]

The γ-ray flux from the source is very high—it is approximately five times that from the Crab Nebula. The luminosity of Cygnus X-3, the distance to which is at least 10 kpc,[90] turns out to be so great that it amounts to 1/50 of the γ luminosity of the entire Galaxy. This is the most remote and most intense of the presently known discrete sources. The observation of this source compels us to regard more cautiously the hypothesis of a diffuse nature of the galactic γ radiation, which up to this time appeared so attractive and almost obvious; only a few sources similar to Cygnus X-3 could explain the radiation peaks observed in the central region of the Galaxy. The hypothesis of a number of discrete sources whose combined flux creates the observed profiles of GGR is again on the scene.

The observed features of Cygnus X-3 show that this source differs greatly both from the discrete γ-ray sources discussed in the preceding sections and from the typical x-ray sources in close double systems. The 4.8-hour period of variation of the intensity of Cygnus X-3 is due most probably to orbital motion in a very close double system (an alternative interpretation[91] apparently encounters definite obstacles[92]). On the other hand, the intense radio and γ radiation indicate a definite role of high-energy particles, which is unusual for x-ray sources in close double systems with accretion of materials into compact objects (neutron stars and black holes).

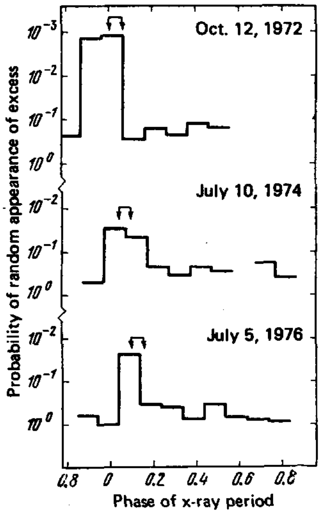

FIG. 14. Distribution of γ rays from the source Cygnus X-3 in phase of the 4.8-hour period for $E_\gamma \geqslant 4\times 10^7$ eV.[135] The arrows show the location of radiation pulses with $E_\gamma \geqslant 10^{12}$ eV.[136]

The unusual nature of the characteristics of Cygnus X-3 has led many astrophysicists to suggest that Cygnus X-3 is a young pulsar (a rapidly rotating neutron magnetic star) located in a close double system (Refs. 94–97).[3)]

The source of energy of a young pulsar is the kinetic energy of rotation of the neutron star, which on rotation of the magnetosphere of the pulsar is converted either into energy of magnetic dipole radiation or into energy of a relativistic stellar wind. In the case of an isolated neutron star, for example the pulsar PSR 0531 in the Crab Nebula, the energy of magnetic dipole radiation or relativistic stellar wind is transported to great distances (~1 pc) and provides generation of electromagnetic radiation over the entire supernova remnant. On the other hand, if the neutron star is located in a close double system together with an ordinary star, then energy dissipation will occur at significantly smaller distances from the pulsar ($\sim 10^{11}$–10^{12} cm) in interaction with the atmosphere of the star, the stellar wind, or electromagnetic radiation.

The hypothesis of existence of a young pulsar rotating in an orbit around an ordinary star permits qualitative explanation of the principal observed features of Cygnus X-3. The relativistic wind flowing out of the pulsar, on encountering the atmosphere of the star, heats it to a temperature $T \sim 10^7\,^\circ$K and initiates the outflow of matter from the surface of the ordinary star. The heated plasma can provide production of the Cygnus X-3 x rays, and the regions of the stellar wind at a distance of the order 10^{12} cm from the surface of the star can be sources of infrared radiation.[98] The γ radiation of Cygnus X-3 must arise as the result of interaction of high-energy particles with the material of the stellar wind or with the electromagnetic radiation of the ordinary star. Finally, production of the radio radiation of Cygnus X-3 must originate in the outer portions of the stellar wind at distances $\sim 10^{14}$–10^{15} cm from the close binary system. The most probable mechanism of production of the radio radiation of Cygnus X-3 is synchrotron radiation of relativistic electrons.[99]

The hypothesis of a young pulsar which comprises part of a close binary system permits a crude qualitative model of Cygnus X-3 to be constructed. A detailed model of this source must explain such phenomena as the variability of the Cygnus X-3 γ radiation,[100] the mechanism of the intense bursts of radio radiation, and the nature of the intensity variations of the x rays and infrared radiation.[101]

[3)] Basko *et al.*[93] made the suggestion some time ago that the x radiation of Cygnus X-3 is the radiation of a pulsar whose directivity diagram does not coincide with the direction to the Earth, reflected from the surface of the principal component of the binary system.

f) The galactic center

The galactic nucleus—the central region of the Galaxy—possesses unique properties and its study presents great interest. Up to this time the study of the galactic nucleus has encountered series difficulties as a result of the fact that the visible radiation of the Galactic Center is concealed from a terrestrial observer by a thick layer of interstellar dust (the extinction of visible radiation reaches 27 stellar magnitudes, in other words, it is attenuated by a factor of 60 billion!). Observation of the Galactic Center in the near infrared region[102] has shown that the concentration of stars in a central region of dimensions ~1 pc is 10^7 times greater than in the vicinity of the solar system. Hoffmann, Frederick, and Emery,[103,104] have shown that the region of the galactic nucleus of diameter ~100 pc is an intense source of long-wavelength infrared radiation; the luminosity of this region is 10^{41}–10^{42} ergs/sec.

Investigation of the nucleus of our Galaxy, which is a thousand times closer to us than the nuclei of other galaxies, can shed light on one of the most crucial problems of contemporary astrophysics—the problem of the nature of the nuclei of active galaxies and quasars. Gamma-astronomy observations of the Galactic Center permit unmasking of an important aspect of the dynamics of galactic nuclei—the role of high-energy particles and their interaction with the interstellar medium.

The data obtained from the satellites SAS-2 and COS-B do not yet permit a definite idea to be obtained regarding the γ radiation of the Galactic Center. In the longitude distribution of GGR an appreciable peak is observed (see Fig. 4) whose width (~4°) agrees with the size of the central cloud of molecular hydrogen ($3° \times 0.5°$). This is consistent with the existence of a γ-ray source associated with the central cloud, the flux of which amounts to $(1-5)\times 10^{-6}$ cm^{-2} sec^{-1}. Such a flux could be provided by the interaction of cosmic rays with the gas if their intensity was 5–10 times greater than that of cosmic rays in the vicinity of the solar system.[105,106]

The value of gamma-astronomy observations of the Galactic Center should grow rapidly as the angular resolution of γ telescopes is increased.

g) *Unidentified discrete γ-ray sources*

The source CG 195+5 is not the only discrete source which has not been identified with known astrophysical objects. In the satellite COS-B as a result of the first, far from complete, analysis of the experimental data, 13 γ-ray sources were observed in the energy range $E_\gamma \geq 100$ MeV.[107] This work[107] utilized the observations of a region covering about 40% of the galactic equator. The basis of the method of distinguishing the discrete sources in the background of diffuse radiation was taken to be an angular distribution function of the discrete source radiation (a "standard profile") determined on the basis of observations of the very intense source CG 263-2 = PSR 0833-45, whose location is known with high accuracy. The standard profile of a source is satisfactorily described by a Gaussian function with a width (FWHM) of 2.5° for $E_\gamma = 100$ MeV. Using the standard profile, Hermsen *et al.*[107] searched the γ map of the sky for an excess of γ rays and, on the basis of the usual procedure adopted in searches for discrete sources,[108] determined the Poisson probability of the excess, the confidence level C of the source, and the γ-ray flux F. In Table IV we have given information on sources for which the confidence level C exceeded 0.95, taking into account all cells of the grid on the γ map. In addition to the reliable discrete sources, in the search a large number of "hot spots" were also observed, excesses with $C < 0.95$, which could be either statistical fluctuations of the background or sources of lower intensity which were not reliably distinguished in this observation.

The number of discrete γ-ray sources discovered by the satellite COS-B has now reached 24.[109b] All of them have been listed in Table V. The sources are broken down into three spectral classes: soft S, medium M, and hard H, depending on their spectrum, which is characterized by a quantity $\varkappa = F_1/F_2$, where F_1 and F_2 are the fluxes in the energy intervals from 50 to 150 MeV and above 150 MeV, respectively. The difference between the spectral classes is quite substantial: the quantity $\varkappa$ changes by a factor of five the transition from class S to class H. Thus, in contrast to the diffuse flux of GGR, which has the same spectrum over all directions in the Galaxy, the fluxes from different discrete sources differ in their energy spectra, which apparently indicates a diversity of types and production mechanisms.

With the exception of the pulsar in Vela, the γ-ray flux from which is 3.3 times that from the pulsar in the Crab Nebula $F_{\rm cr}$, the fluxes of all remaining discrete sources lie in the range 0.2–1.0 relative to $F_{\rm cr}$; $F_{\rm cr} = (2.8 \pm 0.5)\times 10^{-6}$ photons/cm^2-sec.

The discrete sources are distributed near the galactic equator. An exception is the source CG 291+65, which is located at high galactic latitudes and which has been identified with the quasar 3C 273. The remaining

TABLE V.

№	Galactic coordinates ($l^{\rm II}$, $b^{\rm II}$)	Number of observations	Spectral class	$F/F_{\rm Cr}$	Identification
1	65.5–0.0	3	H	0.3	
2	75.0+0.0	1		0.45	Possibly one extended source
3	78.5+1.5	1		1.0	
4	121.0+3.5	1	H	0.2	
5	135.5+1.5	2	M	0.3	
6	176.0–7.0	1	S	0.5	
7	184.5–5.5	2	M	1.00	PSR 0531+21
8	189.0+1.0	1		0.4	Extended?
9	195.5+4.5	2	H	0.9	γ195+5 (SAS-2)
10	263.5–2.5	5	H	3.3	PSR 0833–45
11	312.0–1.5	1		0.45	
12	327.5–0.5	1		0.35	
13	335.5+0.0	1		0.7	
14	21.0+1.0	1	S		PSR 1822–09
15	95.5+4.5	1	H		
16	106.0+1.5	1			
17	219.0–0.5	1	M		PSR 0740+28
18	243.0–2.5	1	H		
19	270.0–1.0	2	S		
20	284.0–1.0	1	H		
21	288.5–0.5	1	M	0.1	3C 273
22	291.0+65	1	M		
23	295.5+0.5	1	M		ρ Ophiuchus
24	353.0+16.0	1	H		

sources are apparently within the Galaxy. Their average latitude is $\Delta b^{II} \approx 2°$, from which it follows that the average distance to them amounts to about 2 kpc (for a thickness of the galactic disk of 70 pc), and the average luminosity for isotropic radiation is 10^{35} ergs/sec.

The question of the contribution of discrete sources to the observed galactic radiation and of the total number of such sources in the Galaxy is of interest. The luminosity of the Galaxy in γ rays with energy more than 35 MeV amounts to 4×10^{38} ergs/sec. The discrete sources observed up to the present time still comprise an insignificant part of the total radiation. However, their number is constantly growing: according to the preliminary data of COS-B,[109b] in the central region of the Galaxy alone, $|l^{II}| \leq 60°$, there are another 15 new sources which have not been listed in Table V. In Ref. 109c, on the basis of the assumed identification of the discovered discrete sources with supernova remnants, the total number of discrete sources in the Galaxy is estimated as 150. Even with a luminosity of each source of 10^{35} ergs/sec, their contribution to the galactic radiation becomes significant. In addition, observations show that there are sources with much greater luminosity, for example, Cygnus X-3, inclusion of which may turn out to be decisive in solution of the question of what kind of radiation is dominant in the Galaxy—the diffuse component or the discrete sources. The possible distributions of discrete sources and their luminosity have been discussed in Ref. 109d on the assumption of dominance of the discrete component with various distributions of discrete sources over the galactic disk. The contribution of unidentified sources as a whole may comprise an appreciable part of the total luminosity of the Galaxy in the γ-ray region.

This fact, together with the dominance of hard γ radiation over x radiation, gives the study of unidentified discrete sources a significant astrophysical interest. In Ref. 109a an attempt was made to identify the discrete sources observed in the satellite COS-B with the x-ray sources observed in the satellites SAS-1, OSO-7, Ariel-5, and SAS-3. In three cases, coincidence was observed between x-ray and γ sources (CG 135 + 1 = 4U 0241 + 61, CG 312 − 1 = 4U 1416 − 62, and CG 327 − 0 = 2A 1533 − 542), but as a result of the low accuracy in determining the coordinates of the γ sources, the statistical reliability of the identified pairs of sources is low.

Vladimirskiĭ[109c] has shown that certain discrete sources coincide with supernova remnants with relatively low spectral exponents $\alpha \leq 0.3$, which may be associated with pulsars with relatively large magnetic fields.

Strong[110] has noted that two of the new sources can be identified with giant H II regions: CG 135 + 1 with the region W 3, and CG 189 + 1 with the region NGC 2175.

The nature of the unidentified discrete sources still remains unclear, but they may be associated with hypothetical γ-ray sources discussed previously in theoretical studies. For example, in Refs. 111–114 the production of γ radiation in accretion onto a black hole was discussed. In the case when accretion of gas is not accompanied by formation of a disk, the temperature of the matter in the vicinity of the black hole can exceed 10^{12} °K. Nuclear collisions in such a hot gas can be accompanied by production of π^0 mesons and generation of γ rays. The luminosity of black holes in the γ-ray region may exceed 10^{34}–10^{35} ergs/sec, and the γ-ray fluxes should amount to 10^{-6}–10^{-7} photons/cm^2-sec.

Discrete γ-ray sources should also be associated with dense interstellar clouds which are penetrated by cosmic rays.[115] The γ-ray flux from a cloud with mass M located at a distance D is

$$F = 1.3 \cdot 10^{-6} \frac{M}{10^6 M_\odot} \left(\frac{D}{1\,\text{kpc}}\right)^{-2}. \tag{13}$$

For the dark gaseous and dust clouds closest to us, the expected fluxes should amount to about 10^{-7} photons/cm^2-sec.

In order to obtain the observed γ-ray intensity of about 10^{-6} photons/cm^2-sec, the mass of a gas cloud located at a distance of 2 kpc must amount to 10^6M. The only source of this type in the catalog of Table V may be CG 353 + 16, which coincides with the complex of gas-dust clouds ρ Ophiuchus. Most of the observed discrete sources cannot be identified with such objects, as the result of the observed variability of the γ rays and the diversity of the energy spectra.

Supernova remnants[116] should also be sources of γ rays arising in the interaction of cosmic rays with the interstellar gas. However, as a result of the low concentration of the gas, the expected flux of pionic radiation of the known supernova remnants—the Crab Nebula, the supernova remnant in Vela, and others—is small.

The observation of a supernova burst in our Galaxy will necessarily be an event of great value in astronomy. The last supernova explosion observed on the Earth occurred in the year 1604—several years before the invention of the telescope. Now, on the other hand, the entire powerful arsenal of contemporary astronomy could be thrown into the observation of a galactic supernova—from the largest radio telescopes, to giant underground (and perhaps also underwater[17]) installations for neutrino detection. Beyond any doubt the cycle of observations of the next galactic supernova will turn out to have a great influence on the development of contemporary astrophysics.

An important role in the observations of the explosion of a galactic supernova should also be played by γ astronomy. In particular, γ-astronomy observations will permit investigation of the question of the production of cosmic rays by a rapidly rotating young pulsar covered by the dense shell of the supernova. The generation of γ rays, neutrinos, and neutrons in the dense supernova shell surrounding a young pulsar has been discussed in Refs. 118–123. In these studies it has been shown that a young supernova remnant which has exploded at a distance of about 10 kpc from the solar system can for a period of several months be a very intense source of γ rays with an intensity several orders of magnitude greater than the most intense of the discrete γ-ray sources observed so far. The γ radiation of a young supernova remnant is produced in the interaction of cosmic rays accelerated by the young pulsar with the material of the shell or with the field of electromagnetic radiation of the supernova. Study of the γ radiation of a young supernova remnant will permit investigation of the mechanism of acceleration of cosmic rays by a young pulsar and determination of the significance of this process in the general picture of cosmic-ray production in the Galaxy. Such sources can in principle also be observed in the explosions of supernovas in neighboring galaxies; in this case their intensity will be at the threshold of sensitivity of contemporary γ telescopes.

The theoretical prediction of Hawking[124] regarding the possibility of quantum-mechanical evaporation of black holes of small mass, produced in the early stage of development of the Universe, has attracted extensive interest among astrophysicists. It has been shown in Refs. 125–127 that the most promising means of observation of black holes of small mass is the search for γ-ray bursts accompanying the final explosive phase of evolution of a black hole. The first observations[128] of short bursts of γ rays were carried out in terrestrial installations for detection of extensive air showers. Such bursts were not observed; an upper limit on the energy of bursts of duration 0.1–1 μsec is 10^{-9}–10^{-10} ergs/cm^2-sec.

4. CONCLUSION

To sum up, the first object of study in the newly mastered γ-ray region has been the Galaxy. As expected, the new method of observation has brought new results which significantly supplement the existing ideas regarding the structure and composition of the Galaxy. We refer first of all to the discovery of an important dynamical feature of the galactic structure—a belt of increased activity at a distance 4–8 kpc from the Galactic Center—and the observation of a new type of galactic population—molecular hydrogen. Note that we are not discussing the more accurate determination of the composition, a second approximation, but rather the discovery of a component which dominates over the Galaxy as a whole, exceeding by several times in concentration the long known atomic hydrogen. It is important to emphasize also that these discoveries have turned out to be possible only as the result of comparison of the data of observations in the radio, infrared, optical, and γ-ray regions, i.e., as the result of the all-wave nature of contemporary observational astrophysics.

Another substantial achievement of γ astronomy in the study of the Galaxy must be considered the discovery of discrete γ-ray sources and the nonuniformity of the distribution of cosmic rays over the galactic disk.

There have been some surprises such as usually accompany the exploration of new spectral regions. In regard to the Galaxy, we can view in this light the unplanned discoveries of γ pulsars, and also the short-duration bursts of soft γ rays; the latter have not been discussed in the present article, for the reason that a separate review has already been devoted to them in Uspekhi Fizicheskii Nauk (Soviet Physics Uspekhi).[137] The nature of the γ bursts has not been discovered up to this time, but there is reason to suppose that they are of galactic origin and consequently can provide additional information on the composition and structure of our stellar system.

The achievements of γ astronomy are quite impressive. In particular, they indicate that γ astronomy has gone over from "potentially important" aspects of astrophysics to currently active areas. However, it must be acknowledged that the potential importance of γ astronomy is still only beginning to appear. Although some of the astrophysical problems which it is hoped to solve with γ astronomy now appear close to solution (for example, the problem of the origin of cosmic rays), nevertheless none of them has yet been solved. This applies also to the questions of the sources of cosmic rays, the spiral arms of the Galaxy, and the possibility of the presence of antimatter in the Galaxy. At the same time appreciable progress has been achieved in most of the investigations mentioned and in the near future we can expect progress in solution of these questions also.

In the near future, research in γ astronomy will be developed still more successfully and will provide new important results. The forerunners of future achievements in this field of research are the continuing successful operation of the γ satellite COS-B, already in its fourth year, the launching of the high energy astronomical observatory HEAO-1, on board which a soft γ-ray telescope is installed, and plans for new experiments to be carried out on space craft and orbiting stations with instruments of much greater sensitivity and better angular and energy resolution than presently operating telescopes.

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