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THE STUDY OF COSMIC γ RAYS

A. M. GAL'PER, V. G. KIRILLOV-UGRYUMOV, B. I. LUCHKOV, and O. F. PRILUTSKIĬ

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CONTENTS

1. INTRODUCTION

THE rapid development of cosmic-ray techniques and methods of detecting electromagnetic cosmic radiation have led to the creation of new divisions of astronomy (infrared, x-ray, and γ-ray astronomy). At the present time the Universe is being studied over a wide range of frequencies from 10^6 Hz, corresponding to radio waves with wavelengths of several hundred meters, to 10^{28} Hz, corresponding to superhigh-energy γ radiation (of the order of 10^{14} eV). An extension in the range of observations, as a rule, is accompanied by discovery of qualitatively new phenomena of nature and frequently leads to an important change in concepts of the structure of galactic and extragalactic cosmic objects.

In this respect the study of cosmic γ rays (CGR) presents substantial interest. γ radiation accompanies interactions of energetic particles with matter and radiation, and annihilation of matter and antimatter, and the intensity of the γ radiation is comparatively simply related to such quantities as the density of the matter, radiation, and cosmic rays in the sources or the density of antimatter in intergalactic space. The study of CGR permits in principle evaluation of such quantities, and in a number of cases (for example, in evaluation of the density of intergalactic cosmic rays) this approach turns out to be the only possible one. The observation of γ radiation from various objects, both galactic (supernova remnants, pulsars, x-ray sources), and extragalactic (quasars, radio galaxies, galaxies with increased activity in their nuclei), in association with observations in other regions, leads us to a deeper understanding of their structure. The results of γ astronomy should help in solution of the problems of cosmic-ray sources and of the mechanism of their production and propagation in interstellar and intergalactic space.

The directions of research in γ astronomy are quite diverse. Among them we should mention measurements in the intensity of diffuse CGR (the isotropic metagalactic and anisotropic galactic components), the search for discrete sources, and the study of secondary γ radiation in the upper layers of the atmosphere. A rather interesting division of γ astronomy is devoted to determination of the composition of celestial objects (the moon, and so forth) from their characteristic γ radiation.[1] This subject lies outside the scope of our review. It is discussed in detail in the work of Gorenstein and Gursky.[2]

γ radiation is defined as photons with energies above 0.1 MeV. The range of energy occupied by γ radiation is so broad that the nature of the origin and the methods of detection of γ rays of different energies differ greatly. Therefore, it is convenient to divide γ radiation into several regions:

1. Soft γ rays (photon energy 0.1–10 MeV) immediately adjacent to hard x rays.
2. Energetic γ rays (photon energy 10–1000 MeV). Most work on γ astronomy has been carried out in the soft and energetic photon regions. This is due to the fact that the expected fluxes of CGR fall off rapidly with increasing γ-ray energy.
3. Hard γ rays (photon energy 1–100 BeV).
4. Superhigh-energy γ rays ($E_\gamma > 100$ BeV). In spite of the extraordinarily small fluxes expected in this region, the interval 10^2–10^4 BeV has been investigated much better than the preceding range of hard γ rays. This situation has arisen as the result of use of an original method of detection of extraterrestrial γ rays of superhigh energy by means of the Cerenkov radiation of showers generated by photons in the atmosphere, proposed by Chudakov et al.[3,4] The technique of detection of Cerenkov radiation from atmospheric showers is discussed in detail in the review of Jelley.[5]

The total number of papers devoted to γ astronomy reaches several hundred. Reviews of earlier CGR studies have been given by Ginzburg and Syrovatskiĭ,[6] Kraushaar and Clark,[7] Hayakawa,[8] Oda,[9] Garmire and Kraushaar,[10] Rossi,[11] Fazio,[12] and Gal'per and Luchkov.[13] Research carried out in recent years has been summarized in the reviews of Duthie,[14] Chuĭkin,[15] Syrovatskiĭ,[16] Pal,[17] Fazio,[18] and Silk.[19] The special reviews of Peterson et al.[20] and Romanov[21] have been devoted to research on soft γ rays. Work on the x rays and γ rays of the Sun has been brought together in the review of Dolan and Fazio,[22] and work on γ radiation in the atmosphere in the reviews of Chuĭkin[15] and Romanov.[21] A review of the experimental methods of CGR research has been given by Kraushaar.[23] For completeness we note that the results of research on cosmic x rays can be found, for example, in the reviews of Syrovatskiĭ,[16] Silk,[19] Friedman,[24,25] and Ginzburg.[27]

The technique of detection of x rays is discussed in detail in the review of Giacconi et al.[26]

The purpose of the present review is to systematize the methods, experimental data, and theoretical studies of CGR, the need for which is due to the large and rapidly growing number of studies in this field which have been carried out recently, and also to the absence in the Soviet literature of a rather complete review on this important field of research.

2. MAIN PROCESSES OF CGR PRODUCTION. INTERACTION OF CGR WITH THE INTERSTELLAR AND INTERGALACTIC MEDIUM

Investigators began to be interested in cosmic γ rays at the beginning of the 1950s. Up to that time preliminary data had been obtained on the composition and spectrum of cosmic rays, and the cross sections for nuclear interactions at high energies had been measured in relativistic proton accelerators. It became clear that the study of CGR can provide valuable information on the interaction of cosmic rays with matter and radiation in galactic and extragalactic sources.

A number of authors (Hayakawa et al.,[28-29] Burbidge and Hoyle,[30] Morrison,[31] Ginzburg and Syrovatskiĭ,[6] and others[32-39]) made preliminary estimates of the γ-ray intensity from the metagalaxy, the galaxy, and from galactic and extragalactic radio sources. These results can be examined in more detail in various reviews.[6,10,12] In these studies made in the early stage of γ-astronomy development, the basic processes for CGR production were suggested.

Cosmic γ rays are produced in interaction of energetic electrons, protons, and nuclei with matter and radiation, in annihilation of matter and antimatter, and in radioactive decay. Table I enumerates the main processes of CGR production and lists their spectral and polarization characteristics, which are necessary in analysis of the spectra of various sources; references are given to papers in which these processes are discussed in detail.

One of the striking features of CGR is their high penetrating power. Our galaxy is practically transparent for γ rays over a wide energy range. Nevertheless, in a number of cases it is necessary to take into account the interaction of CGR with the surrounding medium. We will discuss this question in more detail.

Interaction of γ radiation with the interstellar and intergalactic medium reduces to two processes: Compton scattering by electrons, and pair production

Table I. Main Production Processes

Process	Characteristics of Process	References
Decay of neutral pions produced in nuclear collisions	Spectrum for high γ-ray energies power law with exponent close to that for cosmic rays, for about 70 MeV has a maximum. Polarization is absent.	6, 40–42
Relativistic electron bremsstrahlung	Spectrum shape close to that of radiating electrons. For anisotropic angular distribution of electrons a linear polarization can be observed	6,43 Polarization – 44, 45
Inverse Compton effect	Power law spectrum, exponents of electron and photon spectra related by $\alpha_\gamma = \alpha_e + 1/2$. In scattering polarized radiation by relativistic electrons the scattered radiation can be polarized	6, 43, 46–49 Polarization – 50, 51
Synchrotron radiation	Spectrum the same as in inverse Compton effect. Linear polarization is possible	6, 43, 52
Radiation of excited nuclei	Continuous spectrum with a large number of lines. No polarization	6, 53
Annihilation of matter and antimatter	0.511-MeV line. In annhilation of a proton and antiproton a continuous spectrum arises with a broad maximum in the 100-MeV region. No polarization	6, 54
γ radiation in radioactive decay	Line spectrum. No polarization	55–57
Inverse bremsstrahlung	Arises in collision of fast protons with electrons at rest. Properties similar to ordinary bremsstrahlung	58–61

in the field of electrons, protons (nuclei), and photons occupying galactic and intergalactic space.

The density of gas in the galaxy and metagalaxy is rather low. Compton scattering and pair production in the field of charged particles do not substantially affect the propagation of γ rays from galactic sources and extragalactic objects with small red shifts. Interaction of γ rays with intergalactic gas, however, has played an important role in earlier stages of the expansion of the Universe, when the density of intergalactic gas was higher by several orders of magnitude than the present value. This question is discussed in detail in the papers of Rees[63], Arons and McCray[64], and Syunyaev[65]. Arons and McCray noted that it is possible to observe the most remote discrete sources in the region of soft γ rays (in this region the absorption coefficient for electromagnetic radiation, due to Compton scattering and pair production, is minimal). We note for reference that questions of the connection of the red shift, distance, density of intergalactic gas, and the expansion of the Universe are discussed in detail in the monographs of McVittie[66] and Zel'dovich and Novikov[67].

The density of electromagnetic radiation in the metagalaxy is significantly higher than the density of gas. For example, the density of the so-called residual radiation is 400 cm^{-3}, while the density of intergalactic gas does not exceed 10^{-5} cm^{-3} in order of magnitude. Consequently, at sufficiently high γ-ray energies ($E_\gamma > (mc^2)^2/\epsilon$, where mc^2 is the electron rest energy and ϵ is the average energy of the electromagnetic radiation) the main process for interaction of γ rays with the intergalactic medium becomes pair production in collisions with low energy photons. This question has been discussed in more detail in refs. 46 and 68–73. It is interesting to note that at γ-ray energies above 10^{14} eV, the mean free path of photons is significantly smaller than the galactic dimensions. In this energy region development of unique cascade interactions of γ rays with radiation is possible (for more detail see refs. 72 and 73).

3. METHODS OF INVESTIGATION OF CGR

The γ rays are detected by means of secondary electrons which they produce in interaction with matter: photoelectrons, Compton electrons, and electron-positron pairs. γ radiation of almost all energies can be detected by devices known as γ telescopes, which consist of an anticoincidence counter, a block of matter—for high-energy γ rays this is called a converter, and one or more counters which detect the secondary electrons and determines from them the energy and direction of arrival of the γ ray. This counter or group of counters determines the energy resolution and geometrical factor of the apparatus. Geiger, scintillation, Cerenkov, and semiconductor counters are used. Cerenkov counters, in spite of their small pulse height, are used in many γ telescopes because of their insensitivity to low-energy background particles and the possibility of recording directional fluxes.

Soft γ rays are detected with scintillation counters using NaI(Tl) or CsI(Tl) crystals or by semiconductor germanium-lithium detectors with active (scintillation) or passive (lead) collimators. The converter is the crystal itself. For γ rays of 0.1–1 MeV the energy resolution of detectors with alkali halide crystals is 10–20%, and of detectors with semiconductor crystals—an order of magnitude better. Nondirectional detectors which record radiation in a 4π solid angle are often used. As an example of a nondirectional detector, we have shown in Fig. 1 an apparatus for study of γ rays in the range 0.25–6 MeV in the artificial Earth satellite ERS-18,[74] a satellite for study of the near-Earth environment. The sodium iodide crystal which records the γ rays is protected from charged particles by an anticoincidence scintillation counter on all sides except the end through which it is viewed by the photomultiplier. The signals from the crystal and from the plastic scintillator are connected in coincidence. A layer of plastic scintillator is often placed between the crystal and the photomultiplier which views it, and the crystal is then completely covered by the anticoincidence counter. Separation of the signals from the crystal and the plastic scintillator is accomplished on the basis of the difference in pulse duration.

A detector of this type, supplied with a collimator, will record radiation only in a certain solid angle. The detector aperture, which characterizes its angular resolution, is usually ~30°. When special active honeycomb collimators are used, it has been possible to improve the angular resolution to ~10°.[21] The geometrical factor of a directional detector usually does not exceed 10 cm^2-sr. By decreasing the detector area and collimator entrance window, it is possible to obtain better angular resolution, but in this case both the geometrical factor and therefore the number of γ rays recorded are unavoidably reduced.

This inconsistency between improvement of the angular resolution and increase of the aperture of the apparatus is fundamental for γ telescopes consisting only of counters ("blind" γ telescopes). However, telescopes for detection of energetic γ rays can be made "seeing" by introducing into the telescopes a controllable track detector which records the path of each electron-positron pair, from which it is possible to reproduce the direction of arrival of the γ ray. The track detector most suitable for the purpose of γ astronomy is a spark chamber, since it is simple and

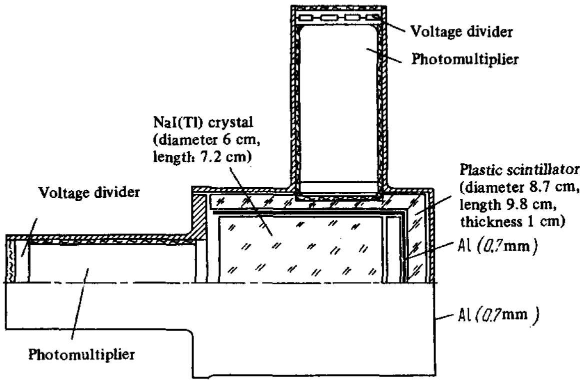

FIG. 1. Diagram of a nondirectional detector for detection of γ rays in the energy range 0.25–6 MeV. [74]

cheap, can be made light and compact, and requires a small expenditure of electrical energy for operation (<1 watt). The angular resolution of spark γ telescopes does not affect the geometrical factor and is determined by the accuracy of reproduction of the γ-ray direction from the tracks of the pair. The angular accuracy in measurement of a charged-particle track in multiplate spark chambers is $\sim 1°$, and in wide-gap spark chamber even $0.1°$.[75] However, the angular distribution of spark γ telescopes at the present time is determined not by this accuracy, but by multiple scattering in the converter. In fact, the converters used at the present time of thickness 0.2–1 radiation length provide comparatively high efficiency for γ-ray detection (15–50%), but broaden the angular resolution up to 3–5° for γ-ray energies $E_\gamma \approx 50$ MeV.

An example of a "blind" telescope is shown in Fig. 2. This apparatus was used by Anisimov, Bratolyubova-Tsulukidze, Grigorov, et al., to detect γ rays with energy $E_\gamma \geq 30$ MeV in the satellite Cosmos 208.[76] Two Cerenkov counters with radiators of Plexiglas, 1, and TF-5 lead glass, 2, form a directional telescope whose backward counting rate, checked in cosmic-ray muons at sea level, is 0.5% of the forward counting rate. The telescope is mounted inside a guard (anticoincidence) cover of plastic scintillator (3, 4) which provides protection against not only charged particles which arrive within the telescope's acceptance angle but also those which hit the sides. The converter consists of a CsI(Tl) plate, 5, of thickness 4 mm and a lead plate 6 of thickness 2 mm. The γ-ray energy is measured in the lower Cerenkov counter, whose radiator contains 2.6 radiation lengths. The efficiency of the anticoincidence cover in the check with muons was $\eta \geq 0.9998 \pm 0.0002$. This value is an important characteristic of blind γ telescopes, since it determines the extent to which the device detects background arising from failure of the anticoincidence counter to count charged particles. Since the desired flux amounts to $\sim 10^{-4}$ of the flux of cosmic-ray charged particles, a value $\eta \geq 0.9999$ is necessary for the effect to equal the background.

Blind γ telescopes similar in their general features to that described have been used by Danielson[77], Cline[78], Duthie et al.[79], Chuĭkin et al.[80], and Sood[81] in experiments at balloon altitudes and by Kraushaar and Clark[82,83], Fazio and Hafner[84], Grigorov et al.[85,86], Bratolyubova-Tsulukidze, Grigorov, et al.[87,88], Clark, Garmire, and Kraushaar[89-91], and Kaplon and Valentine[92,93] in experiments in satellites.

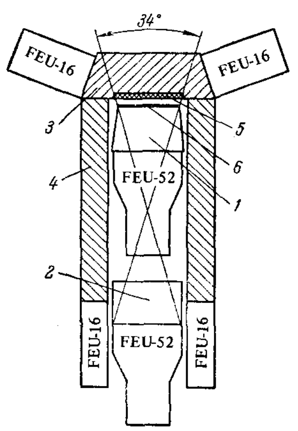

FIG. 2. Diagram of blind γ telescope for detection of γ rays with energies $E_\gamma \geqslant 30$ MeV. [88]

Such severe requirements on the anticoincidence counter are not imposed on spark γ telescopes. Since the final selection is accomplished on the basis of events in the spark chamber, these counters can operate under background conditions 1–2 orders of magnitude greater than the γ-ray counting rate.[94] Use of a spark chamber increases the reliability of operation of a telescope and the trustworthiness of its results, particularly in the case of selection in the chamber of forks produced by electron-positron pairs, for which the probability of imitation is very small, or in the case of detection of an electron shower which can be distinguished from events produced by background nuclear-interacting particles. A multiplate spark chamber is often used also as a converter. Here the upper gaps of the chamber through which the γ rays pass before their conversion in the electrodes supplement and check the anticoincidence counter.

Various modifications of spark chambers are used in γ telescopes: the ordinary multilayer chamber,[95-105] the wide-gap spark chamber,[102-105] the spark chamber with photoemulsions,[106-108] and also various types of spark chambers with automatic readout; the acoustic chamber,[109-111] the wire chamber,[112-114] and the vidicon chamber.[115-117] The use of a given type of spark chamber is determined by the individual tastes of the experimenter and by the energy range of the γ rays and the experimental conditions. Chambers with automatic information readout permit γ telescopes to be installed in unrecoverable objects. In this case all the information from the apparatus, including the number of sparks in the gaps, their coordinates, and so forth, is coded and transmitted to the Earth by telemetry.

Figure 3 shows the spark γ telescope used by Frye and Wang[98,99] in many balloon measurements. A counter telescope consisting of two scintillation counters and one directional Cerenkov counter, in the absence of a signal from the anticoincidence counters, triggers a spark chamber in one of whose plates the

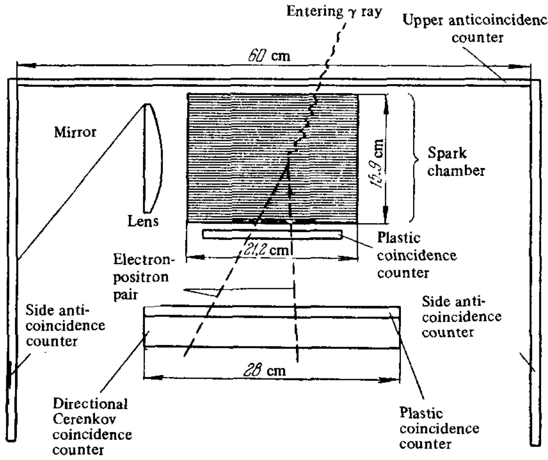

FIG. 3. Diagram of a spark γ telescope for detection of γ rays with energies $E_\gamma \geqslant 50$ MeV. [99]

γ ray is converted. The chamber consists of 30 gaps of 4.8 mm and 31 plates of stainless steel 0.5 mm thick. The efficiency for detection of a 100-MeV γ ray is 32%, and the accuracy in measurement of the arrival angle is ~3°. The apparatus is a γ telescope with large aperture (geometrical factor 175 cm^2-sr) intended for examination of extended portions of the sky in searches for γ rays with energy $E_\gamma \geq 50$ MeV.

The use of spark chambers has permitted a substantial increase in the area-solid-angle factor of γ telescopes. γ telescopes have been built and tested in operation in high-altitude balloons with area-solid-angle factors Γ equal to 126,[115-117] 175,[96-98] and even 1360 cm^2-sr[101] for an angular resolution $\Delta\theta = 1-5°$. Blind γ telescopes, as a rule, have $\Gamma \approx 10$ cm^2-sr for $\Delta\theta \approx 15°$, i.e., they are inferior to spark telescopes by two orders of magnitude in aperture and one order of magnitude in angular resolution. It would appear that such huge deficiencies would lead to rapid abandonment of blind γ detectors. However, the simplicity and small size and weight have permitted them to compete successfully with more highly refined detectors. In fact, it is blind detectors which have been used recently to make important discoveries in CGR. Kraushaar, Garmire, and Clark in the satellite OSO-3 (orbiting solar observatory)[89-91] used apparatus for which the product of the area-solid-angle factor and the γ-ray detection efficiency was $\Gamma\overline{\eta} = 0.5$ cm^2-sr and the acceptance half-angle ~15° to discover galactic γ rays with $E_\gamma \geq 100$ MeV. Good statistics were obtained as the result of operation of the apparatus for one year.

A unique separation of "spheres of influence" has been observed: blind γ telescopes have been used, as a rule, in satellites, where the long duration of the measurements compensates for the small geometrical factor, and spark γ telescopes have been used in high-altitude balloons. This is explained by the fact that the first qualitative studies of CGR did not require high resolution of the telescopes (the satellites themselves did not yet have adequate orientation and stabilization), and also by the fact that the spark-chamber technique applicable to conditions of space flight was rather complex and not yet completely mastered. However, the first steps in use of spark chambers in satellites have already been taken. Cosmos 264 included a γ telescope with multilayer shower and wide-gap spark chambers, whose geometrical factor and angular resolution were respectively $\Gamma \approx 22$ cm^2-sr and $\Delta\theta \approx 4°$.[104,105] A telescope with an acoustic spark chamber operated also in the satellite OGO-5 (orbiting geophysical observatory).[110,111]

Another method of studying CGR is by the nuclear photoemulsion technique. Since it is a true track detector, a photoemulsion has high reliability, easy visualization of the recorded events, and good spatial and energy resolution. However, the absence of a time scale, the lack of controllability, and also the complexity of analysis substantially limit the use of the photoemulsion method of CGR studies. Since they are not competitive with γ telescopes, nuclear photoemulsions are used only where use of γ telescopes is not sufficiently efficient. This situation has occurred first of all in the energy range 10—100 MeV, where photoemulsions have been used because of their high efficiency in γ-ray detection,[118-120] and in the hard γ-ray interval (1—100 BeV), where the small flux has hindered the use of spark γ telescopes. Photoemulsion chambers have been used to study hard CGR at balloon altitudes.[121-124] It should be noted that CGR studies by the emulsion method have led to less definite results than studies with γ telescopes.

In the superhigh-energy γ-ray region, investigations are carried out on the Earth by means of large-area optical mirrors (several square meters) which collect and focus onto a photomultiplier the Cerenkov radiation produced by an electron-photon shower in the upper layers of the atmosphere.

In addition to high-energy cosmic γ rays, similar showers are produced by secondary γ rays and charged particles, which produces a background Cerenkov radiation. Nevertheless, as the result of the good directivity of a telescope (angular resolution ~1—2°), large area, and the possibility of measurements repeated many times, one can hope to identify the excess flux from certain celestial objects as they come into the acceptance cone of the apparatus. The deficiencies of the method lie in the fact that observations can be made only on moonless and cloudless nights.

The Cerenkov γ-telescope method permits detection of CGR from discrete sources in the energy range $E_\gamma = 10^2-2 \times 10^4$ BeV. Investigations of this sort have been made by Chudakov et al.,[3,4] Long et al.,[125] Fegan et al.,[126] Tornabene et al.,[127] Fazio et al.,[128-132] Charman et al.,[133-136] Chatterjee et al.,[137] and O'Mongain et al.[138]

At still higher energies, attempts have been made to obtain information on CGR from data on extended air showers (EAS) with a small number of muons. Apparatus for detection of EAS are located at sea level, occupy an area of several square kilometers, and contain a large number of counters, ionization chambers, and other detectors. This method permits in principle the study of γ rays in the energy range 10^5-10^7 BeV, but has not as yet led to any definite results.[139-141]

4. COMPARABILITY OF EXPERIMENTAL RESULTS: CALIBRATION OF γ DETECTORS

As in any new field of investigation, the spread in individual experimental results of CGR measurements is still rather large. The corresponding values of γ-ray fluxes in the Earth's atmosphere and from definite regions of the sky, measured by different apparatus, differ by several times. The range of energies, determined mainly by the detector threshold energy E_γ, is sometimes established quite arbitrarily. The cause of the large spread in experimental values is often poor statistics of the observations. However, there are cases in which the main cause lies not in statistical fluctuations but in correct calculation of the characteristics of the apparatus: the area-solid-angle factor, γ-ray detection efficiency, and so forth. The uncertainty is aggravated by the fact that these characteristics are not strictly constant quantities, but depend on the energy spectrum and angular distribution of the flux being recorded.

Values of γ-ray fluxes exaggerated as the result of incorrect calculation of apparatus characteristics have been reported in refs. 79, 82, 90, and 91. A particularly striking example is the results of Clark, Garmire, and Kraushaar obtained in the satellite OSO-3.[90,91] The large values of diffuse isotropic and galactic γ-ray fluxes measured in this work were inconsistent with theoretical estimates[6,12] and with the data of other experimental groups.[88,100,114,142] Simultaneous recalibration in an accelerator of a prototype of the γ telescope used in OSO-3 with the apparatus of Fichtel et al.[114] showed that the γ-telescope efficiency assumed previously was substantially underestimated (by about three times!).[143] The recalculated results of Clark et al.[144-146] correspond much better to the theoretical calculations and are in satisfactory agreement with the data of other experiments.

In order to compare the results of different groups and to obtain objective data on the absolute fluxes of CGR, it is necessary to calibrate telescopes in accelerators, which is possible at the present time up to energies of tens of BeV. Calibration enables us not only to determine the detection efficiency of the apparatus for γ rays of various energies and to calculate the geometrical factor and acceptance angle, but also to bring to light various cases of simulation of γ events by nuclear-interacting particles.

Calibration of telescopes in γ rays with energy $E_\gamma > 100$ MeV often is made difficult by the absence of intense beams of monochromatic γ rays. A way out of this situation lies in calibration in beams of monochromatic electrons with subsequent calculation of the efficiency for detection of γ rays by the device. This calculation, as carried out in the work of Volobuev, Gal'per, et al.,[104] includes the experimentally measured electron detection probabilities for the conversion pair components.

Calibration of a γ-telescope energy detector is very important. Energy detectors often consist of counters or spark chambers containing a total of only 3–4 radiation lengths, since use of total-absorption detectors (10–15 radiation length) in experiments outside the atmosphere is hindered by their large weight and size. Because of fluctuations in the initial development of a shower, the energy resolution of spectrometers of this type is rather poor and for a single event amounts to ~50–70%. Nevertheless, spectrometers with poor resolution can be used successfully to study the energy spectra of CGR. The measured spectra are rather smooth and close to a power law

$$N(E) = AE^{-\alpha}, \tag{1}$$

and the experimental problem often consists of determining the exponent α or the deviation from the power law (1). Calibration of the energy detector permits determination of the instrumental function f(x, E), where x is the quantity measured by the detector (pulse height, number of particles in a shower, scattering angle, and so forth) which depends on E. The spectrum R(x) recorded by the apparatus, the instrumental function, and the energy spectrum being measured are related by the expression

$$R(x) = \int_{E_1}^{E_2} N(E)\, f(x, E)\, dE, \tag{2}$$

where E_1 and E_2 determine the energy range of γ rays recorded by the detector. The problem of finding the spectrum N(E) from the known function f(x, E) and the measured distribution R(x) has been solved by Bezus et al.[147] for the case of a power spectrum and by Gal'per et al.[148] for any smooth spectrum.

The method of measuring energy by multiple scattering in a spark chamber has been used by Fichtel et al.[149] The accuracy in the energy measurements is 30% at $E_\gamma = 30$ MeV and 200% at $E_\gamma = 150$ MeV.

In experiments with photoemulsion,[106,107,118-124] the γ-ray energy has been measured in the range 10–1000 MeV from the separation angle of the pair components. The average opening angle of a pair is

$$\bar{\vartheta} \approx \frac{m}{E_\gamma} \ln \frac{E_\gamma}{m}, \tag{3}$$

where m is the electron mass. For $E_\gamma \gtrsim 1$ BeV the energy has been determined by multiple scattering of electrons and from the development of the electron shower.[124]

5. CONDITIONS OF CGR STUDY. ATMOSPHERIC AND LOCAL BACKGROUNDS

Hard electromagnetic radiation with energy above 1 keV is penetrating and not strongly absorbed in matter. For this reason, and also because the γ rays encounter little material in their path, they traverse interstellar and intergalactic distances with practically no absorption.

In the Earth's atmosphere, γ rays are absorbed with an absorption length equal approximately to the radiation length in air (37 g/cm^2), producing secondary electron-photon showers. This results in the fact that even in the upper layers of the atmosphere the flux of CGR is strongly attenuated, and at mountain altitudes it is practically absent. At the same time, the charged component of primary cosmic rays produces in the upper atmosphere a secondary "atmospheric" γ flux which is the background in measurement of CGR. The gradient of the secondary flux of energetic γ rays[95,116] is $\sim 0.6 \times 10^{-3}$ (cm^2-sec-sr-g/cm^2)$^{-1}$. It is easy to show that for an expected CGR intensity of $\sim 10^{-4}$ of the primary cosmic ray intensity, the flux of CGR is comparable with the atmospheric background even at a depth of 0.15 g/cm^2 of residual atmosphere (~70 km). The high background of "atmospheric" γ rays has led to the fact that study of CGR could be begun only during the last ten years as a result of progress in the technique of high altitude balloon flights and satellites, which have permitted γ telescopes to be taken to the top of the atmosphere and beyond.

Balloon studies are carried out at altitudes of 30–40 km, corresponding to 10–3 g/cm^2 of residual atmosphere. The duration of a flight is usually several hours, 2–3 hours being occupied in the ascent, and the remaining time spent in drift at approximately constant depth.

In recent years, longer flights lasting several days have been achieved. Since the magnitude of the "atmospheric" background depends on the intensity of cosmic rays incident at the top of the atmosphere, balloon studies are preferably carried out near the geomagnetic equator.[81,95,99,100,124,150] In Table II we have

Table II. Fluxes of energetic and hard γ rays in upper layers of the atmosphere

Authors	Geomagnetic latitude λ_{gm}	Maximum altitude, g/cm²	Threshold energy, MeV	Flux at maximum altitude	Flux extrapolated to h = 3 g/cm²	Flux extrapolated to top of atmosphere
				10^{-3} (cm²-sec-sr)$^{-1}$		
Cline (1961) [76]	55	8.5	50	7.0±0.7	2.0±0.2	1±3
Duthie, Hafner, et al. (1963) [79]	42	4	60			⩽2
Cobb, Duthie, and Stewart (1965) [95]	17	6.5	100	4.3±0.2	2.0±0.1	
Duthie, Cobb, and Stewart (1966) [94]	42	4.1	50	3.94±0.18	2.9	
Frye and Smith (1966) [97]	42	3.5	30	5.2±0.5	4.5±0.4	⩽5
Chuĭkin, Romanov, and Lenin (1966) [80]	47	9	70	8±2	~3	⩽4
Frye and Wang (1967) [98]	42	2.3	50	3.7±0.4	4.8±0.5	
Fazio et al. (1968) [116]	42	4	100	1.9±0.2	1.4±0.2	
Duthie and Osborn (1968) [150]	−23	3.4	100	3.04±0.15	2.7	
Delvaille et al. (1968) [101]	46	10	1 000	2,2	3	
Fichtel, Kniffen, and Ögelman (1969) [114]	40	3	30 50 100	5.7±0.6 4.8±0.5 3.0±0.4	5.7±0.6 4.8±0.5 3.0±0.4	
Frye and Wang (1969) [99]	42 20	2.5 2.9	50 50			< 0.5 *)
Anand, Daniel, and Stephens (1968) [124]	17	6	50 100 2 000 5 000 10 000 50 000	1.3 0.6 0,26 0.14 0.06 0,03		< 1.3 < 0.6 < 0.26 < 0.14 < 0.06 < 0.03

*At the 95% confidence level.

listed the results of measurements of γ-ray flux in the upper layers of the atmosphere, carried out in high-altitude balloons. When the differences in acceptance angle and threshold energy of the telescopes is taken into account, good agreement is observed between the different results when reduced to the same depth (3 g/cm²). The intensity of the atmospheric γ flux decreases with increasing energy[112] but, strange as it may seem, no dependence is found on the geomagnetic latitude λ_{gm} in the range from 17 to 55°.

The energy spectra of the atmospheric γ flux have been measured by Svensson,[151] Klarman,[118] and Frye et al.[120] in photoemulsions, by Chuĭkin et al.[80] and Kohn et al.[152] by means of scintillation spectrometers, and by Duthie et al.[14,94,95] and Bezus et al.[153] by means of spark chambers. The measured spectrum agrees in its main features with that calculated by Hayakawa et al.[39] and Okuda and Yamamoto,[154] although some discrepancies are observed. Thus, for example, in refs. 14, 94, 95, and 120 an excess of γ rays with energy $E_\gamma < 50$ MeV is observed. Bezus et al.[153] have observed a change in the exponent of the spectrum with altitude: the exponent of the differential power spectrum α changes from 1.93 ± 0.08 at a depth 75–120 g/cm² to 2.46 ± 0.07 at a depth 20–30 g/cm². Measurements of the energy spectra of soft γ rays in the atmosphere have been made by a number of workers.[20,21] Schwartz and Peterson[155] showed that at a depth of 3.5 g/cm² in the range 1–10 MeV the differential spectrum has a power form (1) with an exponent $\alpha = 1.55$.

An interesting aspect of the study of atmospheric γ rays is the search for annihilation γ rays with energy 0.511 MeV and 70–100 MeV carried out by Konstantinov et al.[156] to check the hypothesis of antimatter composition of comets and meteor fluxes. These authors state that measurements in the atmosphere and also in the satellite Cosmos 135 show[157] that there is a definite correlation between the radiation investigated and meteor fluxes.

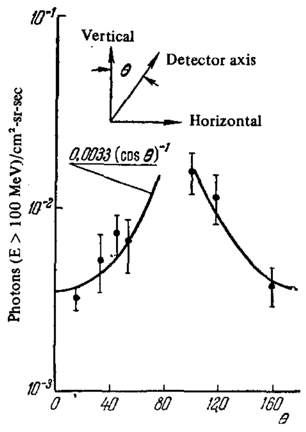

FIG. 4. Angular dependence of atmospheric γ-ray flux with energy $E_\gamma \geqslant 100$ MeV at a height of 3 g/cm² of residual atmosphere. [114]

The intensity of γ rays in the atmosphere varies with the zenith angle of the γ telescope θ. In Fig. 4 we have shown the intensity variation of the flux of γ rays with energy $E_\gamma \geq 100$ MeV at a depth of 3 g/cm^2 as a function of the zenith angle of the telescope axis.[114] The intensity increases as the angle θ increases from zero (the direct vertical flux to the Earth) to 90°. Although the angular measurements in the atmosphere have not been made very accurately, there is a basis for assuming that the largest flux will be observed from the line of the horizon, which at an altitude of 40 km is visible at an angle $\theta_h = 96°$. The albedo flux (coming from the Earth) of atmospheric γ rays falls off with increasing θ. The albedo flux at $\theta = 180°$ at a depth of 3 g/cm^2 agrees within experimental error with the direct flux of atmospheric γ rays.

In satellite studies, the telescope is taken beyond the atmosphere, and the atmospheric background is represented only by the albedo flux. The greatest intensity here is also observed from the horizon line, which for a height of 200 km is visible at an angle $\theta_h = 104°$. Figure 5 shows the angular dependence of the counting rate of a γ telescope in the satellite OSO-3.[91] In this study, γ rays arriving at an angle $\theta \leq 60°$, i.e., at least 40° above the horizon, were assumed to be cosmic rays. The vertical albedo flux ($\theta = 180°$) can be used to check the operation of the apparatus in flight. Table III lists the intensities of the vertical albedo flux with energy $E_\gamma \geq 100$ MeV at a latitude $\lambda_{gm} = 40°$. The albedo flux obtained by Clark et al. in OSO-3 is several times larger than the results of other measurements, which indicates an underestimated efficiency of the apparatus. When the corrected value of efficiency is taken into account, the value of albedo flux in OSO-3 comes into agreement with other measurements.

In addition to the background of albedo γ rays, which can be removed to a considerable degree by appropriate installation of the γ telescope, the local background plays a major role in measurements in satellites. This is due to γ rays produced by cosmic rays in the satellite and in the material surrounding the γ telescope. In Cosmos 264, secondary γ rays produced in the material above the telescope[104,105] were taken into account by use of an external scintillation counter placed outside the satellite within the acceptance cone of the apparatus and whose operation indicated that a recorded γ ray belonged to the secondary background.

The local background increases when the satellite traverses radiation belts and anomalies (for example, the Brazilian anomaly). The high intensity of trapped radiation flux leads to an increase in background not only during traversal of the region of the anomaly but also after leaving it, as the result of residual induced radioactivity in the material surrounding the telescope. This background is particularly high for the soft γ-ray region.[157,158] The detector readings for a certain time after the satellite enters an anomaly are excluded, in order to avoid systematic error.

A measure of the extent to which the recorded flux contains background γ rays is the dependence of the flux on the geomagnetic latitude of observation. Since the primary cosmic rays at satellite altitudes have a characteristic latitude dependence, a similar latitude dependence is observed also in the background fluxes, while the CGR intensity naturally should not depend on the place of observation on the Earth. Figure 6 shows the latitude dependence of albedo atmospheric γ rays and cosmic γ rays measured in the satellite OSO-3.[90]

Table III. Vertical albedo flux of γ rays with energy $E_\gamma \geq 100$ MeV at $\lambda_{gm} = 40°$

Authors	Object	Altitude, km	Vertical albedo flux ($\theta = 180°$), 10^{-3} (cm^{-2}-sec-sr)$^{-1}$
Kraushaar et al. (1962) [82,83]	Explorer-11	300—1100	1.9 ± 0.5
Grigorov Kalinkin, et al. (1966) [85,86]	Proton-1, Proton-2	500	~ 2
Clark et al. (1968) [91]	OSO-3	350	10.5 ± 1.0
Fichtel, Kniffen, and Ögelman (1969) [114]	Balloon	~ 40	3.7 ± 0.8

The amount of latitude dependence (the ratio of the counting rate at the maximum—at high latitudes—and at the minimum—at the geomagnetic equator) permits the degree of background contamination of the γ flux to be taken into account and the primary CGR flux which does not depend on latitude to be extracted, as was done in the work of Valentine et al.[93] and Bratolyubova-Tsulukidze et al.[88]

6. RESULTS OF MEASUREMENT OF DIFFUSE CGR IN BALLOONS. THE γ-RAY FLUX EXTRAPOLATED TO THE TOP OF THE ATMOSPHERE

In many studies of γ rays carried out in balloons, the flux has measured as a function of the depth of residual atmosphere,[78,80,95,99] which has permitted determination of the flux extrapolated to the top of the atmosphere, $h = 0$ g/cm^2. For depths $h \ll l_{nuc}$ and $h \ll l$, where $l_{nuc} \approx 80$ g/cm^2 and $l \approx 37$ g/cm^2 are respectively the nuclear and radiation lengths in air, and the altitude dependence of the secondary atmospheric flux is a linear function of h.[154] Therefore the residual flux of CGR can be obtained by linear extrapolation of the measured points. Figure 7 shows the counting rate of a spark γ telescope with a threshold energy of 100 MeV as a function of the atmospheric depth, measured in one balloon flight by Duthie et al.[14] The points show the total counting rate, and the crosses the counting rate of spurious events, i.e., events without tracks in the spark chamber. It is evident that the finite extrapolated flux is completely ex-

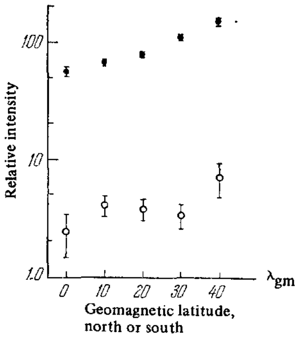

FIG. 6. Intensity of γ-ray flux with energy $E_\gamma \geqslant 100$ MeV as a function of geomagnetic latitude, measured in the satellite OSO-3. [90] ●—atmospheric γ rays; ○—cosmic ($\theta \leqslant 60°$) γ rays.

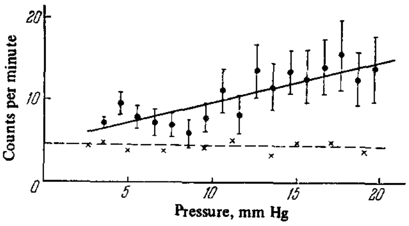

FIG. 7. γ-ray flux with energy $E_\gamma \geqslant 100$ MeV as a function of the depth of residual atmosphere. [14] ●—Total counting rate; X—counting rate of spurious events.

plained by the spurious events. From this we can understand why various studies made with blind γ telescopes led to finite and rather large values of the flux at the top of the atmosphere.[79]

In both the soft and energetic γ-ray regions, similar measurements have not given a definite value for the diffuse CGR flux, but have led only to a calculation of upper limits. In the last column of Table II we have listed the values of γ-ray fluxes extrapolated to the top of the atmosphere. Even in the best studies of this type, made by means of high-aperture spark γ telescopes, no finite flux of CGR has been observed.[99,114] According to Frye and Wang[99] the upper limit of the flux is 5×10^{-4} (cm²sec-sr)$^{-1}$ at the 95% confidence level. In order to measure the flux of CGR by extrapolation to the top of the atmosphere, it is necessary to have high statistical accuracy in measurement of the altitude dependence and, possibly, a more complete knowledge of γ-ray production processes in the upper atmosphere.

In measurements made in balloons by means of nuclear emulsions, the only quantity determined has always been the γ-ray flux at the drift altitude of the balloon and, consequently, only upper limits of the CGR flux could be measured.[118-124] As the result of the good spatial resolution of the photoemulsion and the possibility of reliable separation of γ events from nuclear interaction events, these upper limits of CGR for energies of 50—100 MeV have turned out to be smaller than most other upper limits, which were obtained by the extrapolation method. In addition, the photoemulsion method has been used to obtain the upper limits listed in Table II for the fluxes of hard γ rays with $E_\gamma > 2$, 5, 10, and 50 BeV.[124]

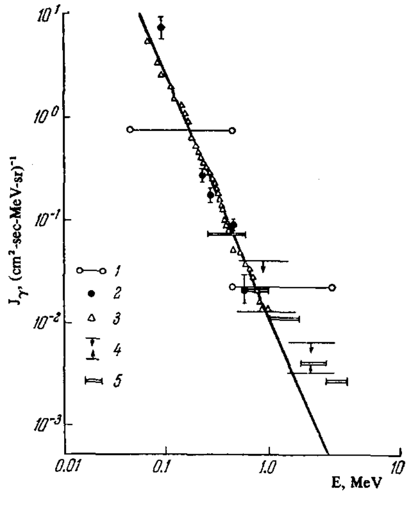

FIG. 8. Differential energy spectrum of cosmic diffuse flux of x rays and soft γ rays according to experimental measurements. 1—ref. 160; 2—ref. 164; 3—refs. 296, 158; 4—ref. 155; 5—ref. 74. Solid line—power spectrum with exponent α = 2.3.

7. RESULTS OF MEASUREMENTS IN SATELLITES. THE ISOTROPIC COMPONENT OF DIFFUSE CGR

More definite results in investigation of the diffuse flux of CGR have been obtained in measurements in the satellites Explorer 11,[82,83] OSO-1,[84] Proton-1 and Proton-2,[85,86] Ranger-3,[158] OSO-3,[89,91,146] ERS-18,[74] OGO-5,[110,111] Cosmos-208,[76,88,142] and Cosmos 264.[104,105]

Figure 8 shows measured differential energy spectra of the diffuse flux of hard x rays and soft γ rays, made mainly with nondirectional detectors.[20,21,74,155,158-165]

In the hard x-ray region (10—40 keV), the upper limit of the anisotropy of the diffuse background is about 4%.[166] In the soft γ-ray region almost no measurements of anisotropy have been made.

As can be seen from Fig. 8, the energy spectrum of diffuse γ rays in the energy region 0.1—1.0 MeV is a power function with an exponent $\alpha = 2.3 \pm 0.2$.[158,163] The spectrum of soft γ rays, consequently, can be considered an extension of the hard x-ray spectrum*. In the energy region 1—6 MeV the situation changes. Vette et al.[74], using the nondirectional detector shown in Fig. 2, have measured a diffuse flux spectrum in the range 0.6—6 MeV which departs appreciably (by 2.5—5.5 times) from the power-law spectrum which we have described. The excess flux is ~0.35 (cm²-sec)$^{-1}$† .

Extrapolation of a power-law spectrum with an exponent $\alpha = 2.3$ to the energetic γ-ray region leads to a flux $\sim 5 \times 10^{-5}$ (cm²sec-sr)$^{-1}$ for $E_\gamma \geq 100$ MeV. In Table IV we have given the measured values of diffuse flux in this energy range. All the measurements give only upper limits of the diffuse flux of CGR. The reason lies in the impossibility of separating the true cosmic-ray events among the background γ rays. The only indication of the cosmic nature of the isotropic flux is the absence of a latitude dependence. However, with the poor statistics of the recorded events, this criterion is extremely ambiguous, as can be seen, for example, from Fig. 6, where for the "cosmic γ rays" ($\theta < 60°$) this dependence may exist within the statistical errors. For a similar reason (absence of convincing arguments in favor of cosmic origin) the results obtained in the satellites Cosmos-208[88] and Cosmos-264[104] can be accepted only as upper limits of the diffuse flux of

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*The background x-ray spectrum has a complex shape. In the energy region 1—20 keV the spectrum is a power law with an exponent $\alpha_1 = 1.7$. [161,167] For energies greater than 20—40 keV the spectrum becomes softer, and its exponent increases to $\alpha_2 = 2.3 \pm 0.2$. However, according to the measurements of Schwartz et al. [167] in the satellite OSO-3, the spectrum exponent in the energy region 40—113 keV is $\alpha_3 = 3.0 \pm 0.3$.

†Measurements of diffuse γ rays in the interval 0.3—3.7 MeV in the satellites Cosmos-135 and -163 [62] are inconsistent with Vette's data and agree with the spectrum extrapolated from the x-ray region.

Table IV. Experimental measurements of diffuse flux of energetic γ rays

Authors	Time of observation	Object	Threshold energy MeV	Intensity 10^{-4} (cm^2-sec-sr)$^{-1}$
Kraushaar et al. [82,83]	April–October 1961	Explorer-11	100	$< 3.3 \pm 1.2$
Fazio and Hafner [84]	March–May 1962	OSO-1	100	$< 20 \pm 20$
Grigorov, Kalinkin, et al. [85,86]	1965	Proton-1, Proton-2	100	$< 5 \pm 3$
Kaplon and Valentine [92,93]	April–March 1967	OSO-3	100	$< 1.67 \pm 0.60$
Clark et al. [145,146]	April-December 1967	OSO-3	100	< 0.3
Bratolyubova-Tsulukidze, Grigorov, et al. [88]	March–April 1968	Cosmos-208	30 50 90 150 500	$< 2.3 \pm 0.5$ $< 1.0 \pm 0.3$ $< 0.53 \pm 0.22$ $< 0.13 \pm 0.09$ $< 0.046 \pm 0.034$
Volobuev, Gal'per, et al. [104]	January 1969	Cosmos-264	200	$< 4.1 \pm 2.3$

CGR. Although a value of the finite flux of CGR is reported by Valentine et al.,[93] everything that has been said above applies completely to their results, which must be considered only as an upper limit.

The results of Bratolyubova-Tsulukidze, Grigorov, et al.[88] are the present-day record upper limits of the diffuse CGR flux. The upper limits obtained in this work are in good agreement with the power spectrum extended from the x-ray region and the soft γ-ray region (Fig. 9). This may mean both that the upper limits measured in Cosmos-208 are close to the true values of cosmic flux, and that in the transition from the x-ray region to the energetic γ-ray region the spectrum becomes steeper.

In order to solve the problem of the intensity, the spectrum, and the degree of isotropy of the diffuse flux, additional experiments carried out with higher-aperture telescopes are needed.

8. GALACTIC ANISOTROPIC DIFFUSE CGR FLUX

γ radiation from the galactic plane (the Milky Way) and in particular from the galactic center, which is located in the constellation Sagittarius (right ascension α = 17 hours 40 minutes, declination $\delta \approx -30°$), has been looked for by many investigators in various energy ranges. Convincing results on the existence of a galactic flux were obtained from the satellite OSO-3 by Clark, Garmire, and Kraushaar,[91] who recorded a maximum in the γ-ray counting rate in the direction of the galactic plane. Since the angular width of the peak is the same as the angular resolution of the apparatus ($\pm 15°$), no conclusion can be drawn from these data on the thickness of the band emitting γ radiation. They are consistent with the assumption of a linear γ-ray source located in the equatorial plane of the galaxy. An anisotropy of γ radiation over galactic longitude was measured, with a maximum in the galactic center where the flux is $(1.2 \pm 0.3) \times 10^{-4}$ (cm^2-sec-rad)$^{-1}$.[144,146] The energy spectrum of the galactic flux was not measured accurately. According to preliminary data[168] it is more energetic than the spectrum of the diffuse flux, and the preliminary data of Kniffen and Fichtel[143] indicate that in the interval 50–150 MeV the spectrum of the galactic flux is flat.

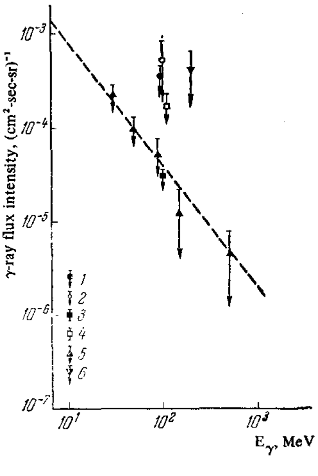

FIG. 9. Experimental measurements of integrated fluxes of energetic CGR. 1–Explorer-11 [83]; 2–Proton-1, 2 [86]; 3–OSO-3 [145,146]; 4–OSO-3 [93]; 5–Cosmos-208 [88]; 6–Cosmos-264 [104]. Dashed line–Extrapolation of the power spectrum (α = 2.3) from the soft γ-ray region.

After publication of the results of Clark et al.[91], results of many experimental groups appeared, based on analysis of both old measurements and new measurements specially designed to check the data of OSO-3.[81,99,100,107,110,111,114] A summary of the measurements of intensity of the galactic component of CGR, together with the time and conditions of the measurements (the object, geomagnetic latitude, angular resolution of the apparatus), is given in Table V. Most of the measurements, if not always quantitatively, at least qualitatively confirm the result of Clark et al.[146] The balloon measurements of Fichtel et al.[114] and Kniffen and Fichtel[143] indicate existence of a γ-ray maximum from the galactic center and are in good agreement with the intensity of the flux measured by Clark et al.[145,146] The measurements of Sood[81], while closely confirming the existence of a flux from the galactic center, do not agree in intensity with the revised result of Clark et al.[146] Excess γ rays from other portions of the galactic plane have been observed from the region of the galactic anticenter by Delvaille et al.[101], and from the region of the constellation Cygnus by Frye and Wang[99], Valdez and Waddington,[107,108] and Hutchinson et al.[111] in the satellite OGO-5. Indication of an excess of γ rays from the galactic plane was obtained also in another detector located on OSO-3.[92]

The results of Frye, Staib, et al.,[100] obtained in a balloon by means of a high-aperture spark γ telescope, are in striking disagreement with these studies. They did not detect an excess flux from the galactic center and give only an upper limit of 3×10^{-5} (cm^2-sec-rad)$^{-1}$ (at the 95% confidence level), which is four times smaller than the flux of Clark et al.[146] This result is most likely erroneous, although we cannot exclude the daring point of view that the result of Frye et al. indicates a variable discrete source located in the direction of the galactic center. At the present time, variability is known in the 3–12 keV region of x-ray sources with periods from tens of minutes (Sco XR-1)[169,170] to several days (a new x-ray source in the sourthern sky[171]) and months (Gen XR-2[172]). The

Table V. Experimental measurements of galactic component of energetic γ rays

Authors	Time of measurement	Object (λ_{gm})	Angular resolution	Threshold energy, MeV	Line source intensity, 10^{-4} (cm^2-sec-rad)$^{-1}$ Galactic center	Anti-center	Cygnus region
Delvaille et al. [101]	April 1966	Balloon (47°)	±1°	1000		6±3 *)	
Frye and Wang [99]	July, September 1966	Balloon (42°)	±2.3	100			0.4±0.2
Fichtel, Kniffen, and Ogelman [114]	December 1966	Balloon (40°)	±3°	100	2.3±1.2	0.4±0,1	
Clark, Garmire, and Kraushaar [143,146]	April, December 1967	OSO-3	±15°	100	1.2±0.3		0.6±0.3
Valdez and Waddington [107]	July 1967	Balloon (42°)	±1	100			3±1.5
Sood [81]	October, November 1967	Balloon (0°)	±25	50	5.0±0.6		
Hutchinson et al. [111]	March, April 1968	OGO-5	±3°	40			4.9±2.1
Frye, Staib, et al. [100]	February 1969	Balloon	±2.3°	50	< 0.3		
Kniffen and Fichtel [143]	October 1969	Balloon	±3°	100	2.0±0.7		

*In units of 10^{-4} (cm^2-sec-sr)$^{-1}$.

increase of intensity at the peak in comparison with the quiescent state amounts to a few times to factors of ten,[171] and in the case of Gen XR-2 several orders of magnitude, so that the entire phenomenon recalls the flash of a supernova in the x-ray region.[172]

In the soft γ-ray region, no experiments have been performed on observation of the galactic component of the diffuse background. A galactic component has been observed in the soft x-ray region (2–18 keV)[166,173], and in the hard x-ray region only upper limits have been obtained.[166,174] The results of measurements of the galactic component of a diffuse radiation are shown in Fig. 10.

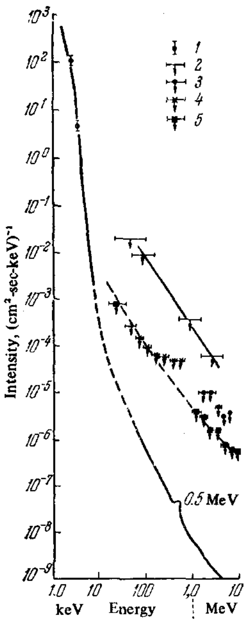

FIG. 10. Energy spectrum of galactic component of diffuse radiation in the x-ray and γ-ray regions. 1–ref. 173; 2–ref. 166; 3–ref. 174; 4–ref. 146; 5–compton model spectrum (α = 1.8) [173].

9. SEARCH FOR DISCRETE CGR SOURCES

Searches for excess radiation over the background from various portions of sky have been carried out over the entire range of γ-ray energies in satellites, balloons, and at sea level. These studies have been carried out both as a systematic survey of the entire sky by γ telescopes with large aperture and rather high angular resolution (telescopes with spark chambers) and as an object-oriented study of possible γ radiation from known cosmic objects. In the latter case, highly directional telescopes with high angular resolution are best suited.

The "searching power" of a telescope can be characterized by the minimal flux from a discrete source $F_{\min}$ which the telescope can distinguish in the background radiation:

$$F_{\min} = A\left(\frac{B\Omega}{\eta S t}\right)^{1/2}, \qquad (4)$$

where B is the intensity of the background isotropic flux, Ω is the solid-angle resolution of the apparatus, η is the γ-ray detection efficiency, S is the detector area, t is the time of observation of an object, and $A \approx 3$ is a constant equal to the value of the positive excess in the standard deviations of the background counting rate at which this excess can be considered statistically demonstrated. Since B, Ω, and η are functions of γ-ray energy, the minimal flux depends also on E_γ.

Let us estimate the minimal fluxes detectable by contemporary γ telescopes. The value of background flux is $B \approx 10^{-3}$ (cm^2-sec-sr)$^{-1}$ in balloon measurements and approximately an order of magnitude lower in satellite measurements. For γ telescopes with a spark chamber, whose angular resolution is $\Delta\theta \approx 1°$, Ω is $\sim 10^{-3}$ sr, and for blind telescopes ($\Delta\theta \approx 15°$)

$\Omega \approx 0.2$ sr. The average efficiency for detection of γ rays with energy $E_\gamma \geq 100$ MeV is $\bar{\eta} \approx 0.2$. Then for the usual present-day telescope with a spark chamber ($S \approx 100$ cm^2) mounted in a balloon, the minimal measureable flux from a discrete source for five hours of observation will be $F_{\min} \approx 5 \times 10^{-6}$ (cm^2-sec)$^{-1}$. The same value of minimal flux is also characteristic of the typical current blind γ telescope in a satellite ($S \approx 10$ cm^2) for an observation time ~1.5 months.

Promising sources for γ rays from the point of view of the possibility of their observation are:

1) Sources of nonthermal radio radiation. Some of them are nebulae produced by explosion of supernovae. Among these are the Crab Nebula (remnant of the supernova of 1054), the radio nebula Vela X, the remnants of the supernovae of Tycho Brahe (1572) and Kepler (1604) and of the supernova of 1005, the loop in Cygnus, Cassiopei A, and so forth.

2) Sources of x rays, the most powerful of which are sources in the constellations Scorpius and Cygnus: Sco XR-1, Cyg XR-1, Cyg XR-2, and so forth.

3) Sources of pulsating radio radiation (pulsars). Some of them have been identified with supernova remnants, for example, the pulsar NP 0532 in the Crab Nebula.

4) Extragalactic sources such as the closest galaxy M31 (Andromeda A) and powerful radio galaxies and quasars: M87 (Virgo A), Cygnus A, and so forth, galaxies with active nuclei (Seyfert and N galaxies).

5) The Sun, particularly during flares.

In Fig. 11 we have shown a sky map with "promising" γ-ray sources plotted on it. Cosmic objects which have already been the subject of a search for γ rays are surrounded by a circle. In order not to complicate the map, we have not shown on it many extra galactic objects from which γ rays have not been searched for. A summary of the upper limits of fluxes from discrete sources is given in Table VI. Systematic studies have been made of ~60% of the celestial sphere in the northern hemisphere and ~40% in the southern hemisphere.[99,100,150] It is apparent that hardly 10% of the promising sources have been studied in the γ region. It is also true, however, that most of them require higher-aperture γ telescopes for investigation.

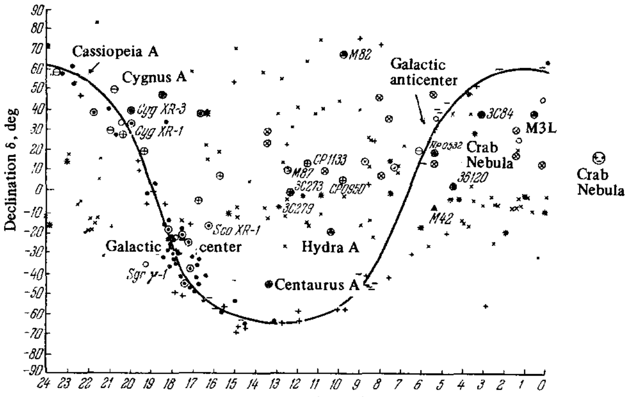

FIG. 11. Sky map of possible discrete γ-ray sources. Solid line—equatorial plane of the galaxy. Supernova remnants; ●—x-ray sources; +—pulsars; X—quasars; ▲—radio galaxies; *—variable radio sources. The sources surrounded by circles have been checked in the γ-ray region.

In Table VI we have shown also the upper limits of fluxes from portions of the sky where excesses of γ rays have at any time been observed. These "sources" are Cornell-1 and -2, Rochester-1, and CWRU-1, observed by the groups of investigators at Cornell, Rochester, and Case-Western Reserve Universities.[94,97,109] The excess flux from the source Rochester-1 in October 1965 according to Duthie et al.[94] amounted to $(1.5 \pm 0.8) \times 10^{-4}$ (cm^2-sec-sr)$^{-1}$. According to the data of Frye and Wang,[98] who studied this region of the sky with a higher-aperture telescope before and after the measurements of Duthie et al., no excess was observed. The upper limit of the flux for $E_\gamma \geq 100$ MeV is 6×10^{-5} and 1.2×10^{-5} (cm^2-sec)$^{-1}$ for January 1965 and July 1966, respectively. Fluxes from the "sources" Cornell-1 and -2 and CWRU-1 also were not observed in repeated measurements.[97,109]

A similar situation exists also in the region of superenergetic γ rays. Excess radiation with energy $E_\gamma \geq 10^{12}$ eV has been observed by a number of workers. From the pulsar CP 1133 fluxes have been observed $J_\gamma \approx 5 \times 10^{-11}$ (cm^2-sec)$^{-1}$ for $E_\gamma \geq 3 \times 10^{12}$ eV (O'Mongain et al.[138]), $J_\gamma \approx 10^{-11}$ (cm^2-sec)$^{-1}$ for $E_\gamma \geq 10^{13}$ eV,[295] and $J_\gamma \approx 2 \times 10^{-12}$ (cm^2-sec)$^{-1}$ for $E_\gamma \geq 7 \times 10^{13}$ eV (Charman et al.[133]). From pulsar CP 0950 a flux of magnitude $J_\gamma \approx 4 \times 10^{-11}$ (cm^2-sec)$^{-1}$ was observed by Chatterjee et al.[137] for $E_\gamma \geq 10^{13}$ eV. However, the subsequent measurements of Fazio et al.[129,130] and Charman et al.[134], made about a year later, did not confirm these results. In Table VI we have listed only the upper limits of the fluxes from these sources.

Although the statistics of the observations are still very poor, such frequent appearance and disappearance of excess fluxes may indicate the existence of variable pulsating sources of γ rays.

This conclusion, possibly, is confirmed by the experimental results of Frye et al.,[100] Kniffen and Fichtel,[143] and Volobuev, Gal'per, et al.[175,176] A discrete source of γ rays with energy $E_\gamma \geq 50$ MeV located in the constellation Sagittarius: $\beta = 288 \pm 3°$, $\delta = -35 \pm 2°$, and named Sgr γ-1 was discovered by Frye et al.[100] from observation of the excess counting rate of a spark γ telescope in two balloon flights in February 1969. The probability of a statistical fluctuation leading to the excess was 8×10^{-4} for the two flights together. The intensity of the flux from SGR γ-1 was $(3 \pm 1) \times 10^{-5}$ (cm^2-sec)$^{-1}$. Kniffen and Fichtel,[143] who studied this portion of the sky in detail in October 1969, observed no excess and obtained only an upper limit of the flux from Sgr γ-1 of 12.4×10^{-5} (cm^2-sec)$^{-1}$ (at the 95% confidence level), which, however, is not in sharp disagreement with the flux of Frye et al.

In the work of Volobuev, Gal'per et al.[176] carried out with a γ telescope on the satellites Cosmos-251 and Cosmos-264, an excess flux of γ rays with energy $E_\gamma \geq 100$ MeV was demonstrated from comparison of the counting-rate characteristics of the apparatus in each of two flights. On the assumption that the radiation of a discrete source was detected, the intensity of the flux is $(6.0 \pm 2.3) \times 10^{-4}$ (cm^2-sec)$^{-1}$. In the region of

Table VI. Upper limits of fluxes from discrete sources

Source	Coordinates						F_γ, 10^{-6} (cm²-sec)⁻¹ ($E_\gamma > 50$ MeV)	F_γ, 10^{-11} (cm²-sec)⁻¹ ($E_\gamma > 10^{12}$ eV)
	α			δ				
	h	m	s	°	′	″		
1. Galactic sources								
Supernova remnants								
Crab Nebula	05	31,5		21	59		17[99]	1.7[133]
IC 443	06	14,6		22	43		20[99]	25[129]
Kepler 1604	17	27,7		—21	25		39[113]	
HB 21	20	44		50	30		21[99]	
Loop in Cygnus	20	48		30	12		11[99]	
Cassiopeia A	23	21,2		58	32		2300[83]	5[3,4]
x-ray sources								
Tau XR-1	5	31		22.1			17[99]	
Sco XR-1	16	15		—15.2			39[113]	
Sco XR-2	17	08		—36.4			26[150]	
Oph XR-2	17	14		—23.5			65[114]	
Sco XR-3	17	23		—44.3			70[150]	
Oph XR-1	17	32		—20.7			39[113]	
Sgr XR-1	17	55		—29.2			39[113]	
Sgr XR-3	17	56		—21.6			39[113]	
Sgr XR-2	18	10		—17.1			12[150]	
Cyg XR-1	19	53		34.5			25[99]	9[129]
Cyg XR-3	19	58		40.4			16[99]	
Cyg XR-2	21	43		38.8			28[99]	
Leo XR-1								31[129]
Pulsars								
NP 0526+21	05	26	10	21	58		17[99]	
NP 0531+21	05	31	31.46	21	58	55	17[99]	1.7[133]
CP *0950+08*	*09*	*50*	*30.76*	*08*	*09*	*48*		1.7[133]
CP 1133+16	11	33	26.9	16	07	35	19[99]	2[130]
AP 1541+09	15	41	10	09	38			10[137]
PSP 1642—03	16	42	25	—03	00			1.6[137]
CP 1919+21	19	19	37.0	21	47	14	16[99]	10[130]
AP 2015+28	20	15	58	28	31		23[99]	
Sun							16[99]	
Moon							24[133]	
2. Extragalactic sources								
Galaxies								
Andromeda Nebula (M31)							18[99]	
Centaurus A							64[114]	
Large Magellanic Cloud							940[83]	
Small Magellanic Cloud							1100[83]	
Hydra A (NGC 4151)							170[83]	10[129]
Radio galaxies								
Virgo A (3C274, M87)	12	28	17	12	40		15[99]	4[129]
Her A (3C348)	16	48	48.0	05	04	35	340[83]	
Cygnus A (3C405)	19	57	44.3	40	35	46	16[99]	5[3,4, 129]
Perseus A (3C84; NGC 1275)	03	16	30	41	20		26[99]	
3C231 (M82)	09	51	43	69	55		600[270]	3[129]
3C458							100[270]	
NGC 5236							280[270]	
NGC 2782							290[270]	
NGC 7469							100[270]	
NGC 7714							100[270]	
Quasars								
3C9	00	17	49.8	15	25	16	6[101]	
3C47	01	33	40.3	20	42	16	30[99]	
3C48	01	34	49.8	32	54	20	30[99]	
3C138	05	18	16.5	16	35	26	50[97]	
3C147	05	38	43.5	49	49	43	25[99]	
3C181	07	25	20.3	14	43	47	120[97]	
3C186	07	40	56.6	38	00	31	30[97]	
3C191	*08*	*02*	*03.7*	*10*	*23*	*58*	*110*[97]	
3C196	08	09	59.3	48	22	08	26[99]	
3C208	08	50	22.7	16	58	15	130[97]	
3C273	12	26	33.35	02	19	42,0	18[99]	7[129]
3C286	13	28	49.7	30	45	59	34[99]	
3C287	13	28	16.1	25	24	37	13[99]	
3C380	18	28	13.3	48	42	39	25[99]	
3C345	16	41	17.7	39	54	11		11[129]
3C245	10	40	06.1	12	19	15		29[129]
3. Unidentified sources								
Cornell-1	0,45			48.5			17[99]	
Cornell-2	1,5			28.5			51[99]	
CWRU-1	5,55			39.1			25[99]	
Rochester-1	20,25			35			14[99]	

the possible location of the source, which is bounded by the coordinates $\alpha = (3.6-5.0)^{\mathrm{h}}$, $\delta = 4-9^\circ$, there are two "promising" γ sources: quasar 3C93 and N-galaxy 3C120. As follows from an analysis made by Volobuev et al.[176], the most probable source of the excess γ radiation detected is 3C120 ($\alpha \approx 4.5^{\mathrm{h}}$, $\delta \approx 5^\circ$)—a powerful source of infrared radiation[177,178] and a variable irregular shortwave radio source.[179,181] The measurements of Volobuev et al.[176] were made at the time of the most intense flares of radio radiation of 3C120 in recent years (October and November, 1968).

In study of pulsars, attempts have been made to observe pulsating γ rays with a period equal to the period of the radio radiation[130,133,134,137,182]; here it was assumed that pulsating γ radiation arises as the result of interaction of protons accelerated in the pulses with the material of the sources.[183-185] Except for the work of Vasseur et al.,[182] which is discussed below (Sec. 10), searches for pulsating γ rays have not given a positive result.

A particularly large number of studies have been devoted to the search for γ rays from the Crab Nebula (Taurus A), the radio sources Cygnus A and Virgo A and the Sun in view both of the great importance of these objects for astrophysics and the very high γ-ray fluxes expected from them. The results of these studies are discussed below.

10. γ RAYS FROM THE CRAB NEBULA

X rays from the Crab Nebula were discovered by Clark et al.[186] in the energy range 15—62 keV. The hard x-ray and soft γ-ray region has been studied by Peterson et al.,[20,187,188] Haymes et al.,[189] Grader et al.,[190] and Frost et al.[191] The energy spectrum of the radiation in the range 35—560 keV is described by the power law[189]

$$\frac{dN}{dE} = (7.1 \pm 2.8)\, E^{-2.19 \pm 0.08}\, (\mathrm{cm}^2\text{-sec-keV})^{-1} \qquad (5)$$

which is in good agreement with most of the results. Above 0.5 MeV the studies which have been made give only upper limits of the flux:

$F_\gamma < 7 \times 10^5\ (\mathrm{cm}^2\text{-sec})^{-1}$ for $E_\gamma = 0.49-0.65$ MeV,
$F_\gamma < 4.5 \times 10^{-5}\ (\mathrm{cm}^2\text{-sec})^{-1}$ for $E_\gamma = 0.65-0.77$ MeV,[191]

and

$J_\gamma < 1.7 \times 10^{-3}\ (\mathrm{cm}^2\text{-sec-MeV})^{-1}$ at $E_\gamma = 1$ MeV,
$J_\gamma < 1 \times 10^{-3}\ (\mathrm{cm}^2\text{-sec-MeV})^{-1}$ at $E_\gamma = 5$ MeV,[192].

Pulsating x rays from pulsar NP 0532 located in the Crab Nebula were recently discovered by Fritz et al.[193] and confirmed by Bradt et al.,[194] Fishman et al.,[195] and Floyd et al.[196] (see also ref. 197)*.

The spectrum of x rays and soft γ rays of the Crab Nebula joins smoothly onto the spectra of optical and radio radiation, which have the same power law. This permits the conclusion to be drawn that the entire range of electromagnetic radiation of the Crab Nebula from 10^8 to 10^{20} Hz is synchrotron radiation.[189] According to this assumption there must exist in the Crab Nebula a magnetic field with an average value of the order of 10^{-4} Oe and a flux of electrons accelerated to an energy of 10^{14} eV.

Extrapolation of the measured power-law spectrum to the energetic γ-ray region gives a flux of $(1.5 \pm 1.0) \times 10^{-5}\ (\mathrm{cm}^2\text{-sec})^{-1}$ for $E_\gamma \geq 50$ MeV. This extrapolated flux value is consistent with results obtained in the search for γ rays in this energy region, which have been summarized in Table VII. In most of the studies, only upper limits of the flux have been determined, and the most reliable of them for $E_\gamma \geq 30-100$ MeV amount to $(2-5) \times 10^{-5}\ (\mathrm{cm}^2\text{-sec})^{-1}$.

A finite flux of energetic γ rays from the Crab Nebula was recorded by Vasseur et al.[182] by means of a spark chamber in a balloon. By measuring the time of arrival of the γ ray with an accuracy of 1 msec, Vasseur et al. were able to identify a pulsating component of γ rays with a period the same as for the radio, optical, and x-ray radiation of pulsar NP 0532 (~33 msec).[193-196] The intensity of the pulsating part of the flux of γ rays with energy $E_\gamma \geq 50$ MeV is $\sim 10^{-5}\ (\mathrm{cm}^2\text{-sec})^{-1}$, which is in agreement with the upper limits of other investigations and with the value of the extrapolated flux*.

In study of the Crab Nebula by γ telescopes on the Earth by means of Cerenkov radiation of the upper atmosphere, Fegan et al.[126] recorded an excess flux of magnitude $1.5 \times 10^{-10}\ (\mathrm{cm}^2\text{-sec})^{-1}$ for energies $E_\gamma \geq 2 \times 10^{12}$ eV. More accurate data obtained by Fazio et al.[129,130] a year later in the world's largest apparatus of this type did not confirm this result.

11. γ RAYS FROM THE EXTRAGALACTIC SOURCES CYGNUS A (CA) AND VIRGO A (VA)

The extragalactic radio sources Cygnus A (3C405) and Virgo A (3C274 or M87) have been studied repeatedly in the x-ray and γ-ray regions. The x-ray source Vir XR-1 has been identified with VA and is the first reliably established extragalactic source of x rays.[198,199] The x-ray spectrum of VA has not been accurately established, but there are indications that there is a single power law for the entire spectrum from VA (from radio to x-ray) with an exponent $\alpha \approx 1.65$.[199-201] No x rays from CA have been found. The upper limit of the flux in the energy range 2—5 keV is $0.03\ (\mathrm{cm}^2\text{-sec})^{-1}$.[202] Haymes et al.[203] have reported observation of soft γ rays (up to 0.45 MeV) from the x-ray source Cyg XR-1, which is located not far from CA but which is, apparently, an intragalactic source. In the energetic γ-ray region no flux has been reliably established either from CA or VA. The upper limits of the γ-ray fluxes with $E_\gamma \geq 50$ MeV are $1.6 \times 10^{-5}\ (\mathrm{cm}^2\text{-sec})^{-1}$ for CA and 1.5

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*Hillier et al. [146] have observed pulsing γ-rays from the Crab Nebula in the range 0.6—9 MeV. The flux of the pulsating component is 2.5×10^{-8} erg/cm²-sec. It is interesting to note that the ratio of the intensities of the pulsating and constant components of the hard radiation of the Crab Nebula increases with increasing photon energy.

*Charman and White [298] and Delvaille and McBreen [299] point out the inadequate statistical basis of the work of Vasseur et al. On the other hand, experimental indications of the existence of a pulsating flux of γ rays with $E_\gamma \geqslant 10$ MeV from NP 0532 are contained in the work of Kinzer et al. [226]

Table VII. γ-radiation of Crab Nebula

Authors	Time of observation	Object (λ_{gm}, h)	Angular resolution	Threshold energy MeV	Flux, 10^{-4} $(cm^2\text{-}sec)^{-1}$	Flux from Crab Nebula region, 10^{-4} $(cm^2\text{-sec-sr})^{-1}$
Kraushaar, Clark, and Garmire [82,83]	March–October 1961	«Explorer-11»	±17°	50	< 6.6 *)	
Frye and Smith [97]	February 1964	Balloon (42°, 3.5 g/cm^2)	2±2,5°	30	< 1.5 *)	
Cobb, Duthie, and Stewart [95]	April 1965	Balloon (17°, 6.5 g/cm^2)	2±2°	100	< 0.49 *)	
Delvaille et al. [101]	April 1966	Balloon (46°, 10 g/cm^2)	±1°	1000	< 0.12 *)	6±3
Fazio et al. [116]	May 1966	Balloon (42°, 4 g/cm^2)	±5°	100	< 0,31 *)	
Frye and Wang [99]	July–September 1966	Balloon (42°, 2.5 g/cm^2; 20°, 2.9 g/cm^2)	±2.6° ±1.3° ±1°	50 150 500	< 0.17 *) < 0,09 *) < 0.05 *)	
Fichtel, Kniffen, and Ögelman [114]	February 1967	Balloon (42°, 3 g/cm^2)	±5° ±3°	30 100	< 2.7 *) < 1.8 *)	
Clark, Garmire, and Kraushaar [91,146]	April, December 1967	OSO-3	±15°	100	< 0.5 *)	0.4±0,1
Fegan et al. [126]	Winter 1966–1967	Cerenkov telescope	±1°	$2\cdot10^6$	$1.5\cdot10^{-10}$	
Vasseur et al. [92]	July, September 1969	Balloon	~ 2°	50	0,1	

*At the 95% confidence level.

× 10^{-5} (cm^2-sec)$^{-1}$ for VA (see Table VI). The upper limit for VA in the region $E_\gamma \geq 50$ MeV lies significantly below the extrapolation of the x-ray spectrum.[99]

In some studies, an excess energetic γ-ray flux has been recorded from regions located not far from CA. In addition to the excess flux of Duthie et al. (Rochester-1)[94] already discussed, an indication of the existence of a flux from a region close to CA was obtained by Clark et al. In OSO-3,[91,146] and by Valdez and Waddington[107-108] and Frye and Wang[99] in balloons. This excess radiation is regarded by these authors as part of the flux from a linear source in the galactic plane (see Table V). However, the poor angular resolution of the instruments themselves and the inaccuracy in determination of their location in space do not permit certain rejection of the idea that this excess flux may be associated with radiation from CA. The same remark must be made also in regard to the measurement of the linear source near the anticenter, which, because of the inaccuracy in its absolute positioning in the sky, may be confused with a discrete source in the Crab. On the other hand, the galactic radiation is a background which hinders observation of the flux from discrete sources located near the galactic plane, such as the Crab Nebula and CA. In this sense a convenient location is occupied by the source VA, which is located far from the galactic equator. Excess radiation from the region of VA has been observed by Fichtel et al.[114] by means of a large wire spark chamber in a balloon.

The deficiency of all observations of excess flux in the region from CA to VA is their poor statistical accuracy. As a rule, the effect does not exceed two standard deviations and, consequently, may arise as the result of a statistical fluctuation.

12. γ RADIATION FROM THE SUN

Radiation from the Sun occupies a special place in studies of CGR, since it serves as the solution of quite different problems than the study of CGR from remote space. At the same time, both in production processes and in methods of study, the γ radiation from the Sun has no basic difference from the radiation of any other cosmic source.

Investigation of the Sun is technologically quite convenient in view of the possibility of achieving accurate orientation toward it of telescopes, using following systems, and utilizing the day-night effect for nondirectional detectors. In spite of these advantages, no x rays or γ rays from the quiet Sun have been observed in the range 0.01–10 MeV. The upper limits measured for the flux by Schwartz and Peterson[155], Peterson et al.,[188,192] and Frost et al.[191] are: 0.05 (cm2-sec)$^{-1}$ for $E_\gamma = 0.16$–0.8 MeV and 0.02 (cm^2-sec)$^{-1}$ for 0.8 MeV. Measurements of γ-ray lines from the sun have also led only to establishment of upper limits, which are 0.005 (cm^2-sec)$^{-1}$ for $E_\gamma = 2.22$ MeV (the line arising in np capture)[158,204] and 0.014 (cm^2-sec)$^{-1}$ for $E_\gamma = 0.511$ MeV (the positron annihilation line).[158,191]

Figure 12 shows the calculated spectrum of x rays and soft γ rays from the quiet Sun[22] and the measured upper limits.

The limits of the flux of solar energetic γ rays with energy $E_\gamma \geq 50$ MeV measured in satellites and balloons are given in Table VIII. It is interesting to

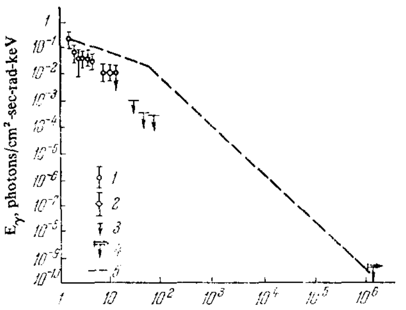

FIG. 12. Differential energy spectrum calculated by Dolan and Fazio [22] of x rays and γ rays from the quiet Sun, and experimental measurements. 1–ref. 297, 2–ref. 155, 3–ref. 192, 4–ref. 191, 5–ref. 192.

note that none of these studies have revealed excess γ rays from the quiet Sun similar to the excess fluxes from the regions of the Crab Nebula, Cygnus A, and Virgo A, although the statistics of the observations are approximately the same in all cases. The best upper limit of the γ-ray flux from the quiet Sun, determined by Frye and Wang,[99] is 1.6×10^{-5} $(\text{cm}^2\text{-sec})^{-1}$.

While the radiation level of the quiet Sun has not yet been measured, increase in the flux during solar flares has been recorded. Peterson and Winkler[205] observed an 18-second rise in the flux of γ rays with energy $E_\gamma = 0.2\text{--}0.5$ MeV at the time of the peak of an optical flare in 1958. Cline et al.[206] detected a γ-ray flux with energy in the range 0.08–1 MeV whose intensity at the maximum exceeded 300 $(\text{cm}^2\text{-sec})^{-1}$ during the flare of July 7, 1966. At high γ-ray energies, no flux has been detected from the Sun even during flares. Thus, Frye and Wang observed no flux of solar γ rays with $E_\gamma \geq 50$ MeV during two subflares,[99] and Fazio et al.[117] determined only an upper limit of the flux, equal to 6×10^{-3} $(\text{cm}^2\text{-sec})^{-1}$ for $E_\gamma \geq 100$ MeV for a class 2+ flare.

13. INTERPRETATION OF THE RESULTS OF CGR STUDIES

As can be seen from the preceding sections, the results of research on cosmic γ rays are rather indefinite and sometimes even contradictory. In spite of this, important conclusions can already be drawn from the results obtained in regard to a number of cosmological problems (estimates can be made of the density of metagalactic cosmic rays, and of the density of antimatter in the Universe) and our ideas can be clarified regarding processes occurring in certain cosmic objects (radio galaxies, quasars, supernova remnants, and so forth). In this section we will discuss astrophysical applications of the results of CGR research, models explaining the origin of various components of cosmic γ rays, and the experiments which are most important, from our point of view, for verification of various models.

Table VIII. Experimental measurements of energetic γ rays from the sun

Authors	Time of observation	Object (λ_{gm}, h)	Threshold energy E_γ, MeV	Flux, 10^{-4} $(\text{cm}^2\text{-sec})^{-1}$
Fazio et al. [116]	May 1966	Balloon	100	< 0.74
Frye and Wang [99]	July, September 1966	Balloon (42°, 3 g/cm²)	50	< 0.16
Fichtel et al. [113]	September 1966	Balloon (47°)	30	< 0.24
Duthie and Osborn [150]	November 1966	Balloon (23°, 3.4 g/cm²)	50	< 0.44
Kaplon and Valentine [99,93]	March–April 1967	OSO-3	50	< 0.22
Fichtel, Kniffen, and Ögelman [114]	February 1968	Balloon (42°, 3 g/cm²)	30 100	< 1.3 < 0.38

A. The Isotropic Component of Diffuse CGR

It is natural to identify the isotropic component of CGR with radiation of the metagalaxy (or in the extreme case to consider it as an upper limit of the intensity of metagalactic γ radiation). The importance of study of metagalactic γ rays for solution of cosmological problems has already been emphasized in early work on γ astronomy.[6,10] The high penetrating power of γ rays, the direct connection between the intensity of the radiation and the density of metagalactic cosmic rays (or antimatter), the transfer of an appreciable part of the energy of cosmic rays (or energy released in annihilation) to the γ rays produced—all of these factors make γ rays a unique source of information on interactions of intergalactic cosmic rays with intergalactic gas and annihilation of matter and antimatter in the galaxy and metagalaxy. The upper limits to the intensity of isotropic diffuse CGR obtained in recent studies,[89-91,144,207] permit definite conclusions to be drawn on the density of antimatter in the galaxy and metagalaxy and the energy density of metagalactic cosmic rays.

We will use the results of Kraushaar et al., corrected after recalibration,[145] to estimate the density of antimatter in the Universe (for more detail see ref. 208). The intensity of γ radiation accompanying the annihilation of antimatter in intergalactic gas is given in order of magnitude by

$$F \sim \frac{1}{4\pi} R_H n\tilde{n}\langle\sigma v\rangle, \tag{6}$$

where $R_H \approx 10^{28}$ cm is the Hubble radius of the metagalaxy, n and $\tilde{n}$ are the densities of matter and antimatter, respectively, $\langle\sigma, v\rangle \approx 10^{-15}$ cm²/sec is the averaged product of the annihilation cross section and the relative velocity of the particles. Consequently, the upper limit to the product of the densities of matter and antimatter in the intergalactic gas is approximately 10^{-17} cm^{-6}. If the density of intergalactic gas is 10^{-5} cm^{-3}, the density of antimatter must be seven orders of magnitude smaller. This result presents considerably difficulty for charge-symmetric models of the Universe. A detailed analysis of this question has been given by Steigman.[208]

The upper limits to the intensity of the CGR isotropic component permit an upper limit to be determined also for the product of the density of intergalactic gas and the energy density of metagalactic cosmic rays. This question has been discussed in detail by Ginzburg,[209,210] Rosental' and Shukalov,[211] and Stecker.[212,213] From the upper limit obtained by

Kraushaar et al.[145] it follows that for an intergalactic gas density equal to the critical value, the metagalactic cosmic-ray energy density cannot exceed 10^{-2} eV/cm^3—a value two orders of magnitude smaller than the energy density of galactic cosmic rays. It should be noted that at the present time measurements have been made of the background radiation in the energy region 30—50 MeV,[207] which permits an estimate to be made of the density of metagalactic cosmic rays also in the cosmological model of Lemaitre (for more detail see ref. 209).

It is interesting to note that from the intensity of isotropic x rays it is possible to obtain an upper limit for the energy density of metagalactic electrons with energies greater than several giga-electron-volts.[214,211,215] According to Rozental' and Shukalov[211] the energy density of metagalactic electrons is at least four orders of magnitude smaller than the energy density of galactic electrons.

Indirect estimates of the density of metagalactic cosmic rays[209,210,216,200] lead to a similar result—the density of metagalactic cosmic rays should be several orders of magnitude lower than for galactic cosmic rays.

Let us now consider the question of possible sources of isotropic γ rays. In the energy region 0.1—1.0 MeV the spectrum of isotropic γ rays is an extension of the spectrum of hard x rays.[158] Therefore we should expect that the nature of the soft γ rays and hard x rays is the same and that they are produced in the same sources. The complex question of the nature of the sources of x rays is beyond the scope of our review. Various approaches to this question are presented by a number of workers.[19 217-223]

In the energy region from 1 to 6 MeV the situation becomes more complex. According to the results of Vette et al.[74], the intensity of background radiation in this region is appreciably greater than that extrapolated from the hard x-ray region. Since the measurements were made with a nondirectional detector, the nature of the radiation is not clear. However, as the authors state, metagalactic origin of the background radiation in this region is most likely. Explanation of the metagalactic origin of the radiation measured by Vette et al., however, encounters great difficulties. For example, the hypothesis of Clayton and Silk[224] regarding radiation in lines during supernova flares and the hypothesis of Brown[61] on inverse bremsstrahlung of metagalactic cosmic rays, as has been shown by Prilutskiĭ and Rozental'[60] and Syunyaev[225], are in direct contradiction with experiment. The hypotheses of Stecker[277] and Rozental' and Shukalov[211] on the pionic origin of metagalactic γ rays in the region 1—6 MeV are consistent with measurements of background radiation in the range 30—50 MeV[207] only for a rather soft spectrum of metagalactic cosmic rays ($\alpha > 3.2$). Syunyaev[225] has proposed that the excess background radiation in the energy region 1—6 MeV is due to radiation of a relativistic plasma surrounding sources of infrared radiation (see also refs. 227 and 228). However, the interaction of relativistic plasma with a magnetic field and with radiation, which is not taken into account in the work of Syunyaev and collaborators,[225,227,228] substantially changes its properties, and therefore the question of the validity of Syunyaev's hypothesis requires additional study (see, for example, the paper by Ochelkov et al.[229]).

As can be seen, the results of Vette et al. have not yet received an unambiguous theoretical interpretation. It should be noted that measurements of background radiation in this region are rather complicated, and repetition of the measurements of Vette et al. with a directional detector must be considered one of the most necessary experiments on study of the background γ radiation.

At high energies ($E_\gamma > 10$ MeV) it is evidently premature to raise the question of the origin of the background radiation. The upper limits obtained for the intensity of isotropic background radiation are still consistent with the assumption of identical nature of the x rays and γ rays. It can be noted that the combined radiation of all galaxies (if they radiate in the γ region as much energy as our galaxy) is at least an order of magnitude lower than the upper limit of intensity obtained by Kraushaar et al.[230]

B. The Galactic Component of Diffuse CGR

Estimates of the galactic γ-ray intensity made by several workers (see, for example, refs. 6, 10, and 38) have shown that the main contribution to galactic γ radiation in the energy region near 100 MeV must be from γ rays from decay of neutral pions produced in interaction of cosmic rays with interstellar gas. However, the measurements of Kraushaar et al.[91] have shown that the observed intensity exceeds the theoretical value by more than an order of magnitude. This discrepancy lay far beyond the limits of error of the initial data (the density of interstellar gas and the intensity of galactic cosmic rays), and several alternative models have been advanced to explain the high intensity of galactic γ rays. However, recent experimental data (the reduction in the value of the galactic γ-ray flux given by Kraushaar et al. after recalibration of the apparatus[145,146], measurements of the galactic component of background radiation in the x-ray region,[166,173,174] and the spectral characteristics of the background radiation in the range 50—100 MeV[143]) apparently argue in favor of a pionic origin of galactic γ radiation in the energy region greater than 50 MeV. We will discuss this question in more detail.

The models advanced to explain the galactic component of diffuse γ rays can be divided into three groups:

1) Decay of neutral pions produced in collisions of cosmic rays with interstellar gas. This model is characterized by presence of a broad peak in the spectrum in the energy region near 70 MeV. The measurements of Kniffen and Fichtel[143], according to which the spectrum of galactic γ rays in the region 50—150 MeV is flat, apparently support the pion model. According to the calculations of Stecker et al.,[231,232] in order to explain the corrected results of Kraushaar et al. it is necessary to assume that the density of interstellar hydrogen is approximately 1 atom/cm^3. This is somewhat greater than the density of atomic hydrogen in the galaxy, which is 0.3—0.5 cm^{-3}.[233] This disagreement can be removed by assumption of an increased concen-

tration of cosmic rays in the vicinity of the galactic center. In addition, it is not excluded that a significant part of the interstellar hydrogen is in molecular form,[232] which apparently is confirmed by recent measurements.[234] Final verification of the pionic hypothesis can be accomplished by more accurate spectral measurements of galactic γ rays in the region 30–1000 MeV.

2) Inverse Compton effect of relativistic electrons and the residual or infrared radiation. Felten and Morrison[217] have discussed this model in detail for the residual radiation. Explanation of the results of Kraushaar et al. in terms of this model requires too high a density of relativistic electrons in the galaxy, considerably exceeding the density observed near the Earth.[235] A number of authors (see refs. 145, 236–238) have attempted to overcome this difficulty by considering the inverse Compton effect of galactic electrons and the intense infrared radiation observed by Shivanandan et al.[239,240]*. However, the results of measurements of the galactic component of background x radiation[166,173,174] apparently are incompatible with the Compton model. Figure 10 shows the results of measurements of the galactic component of background radiation in the energy region 1 keV-150 MeV. It can be seen from the figure that the power spectrum of the Compton model (shown by the dashed line) is inconsistent with the results of spectral measurements of the galactic component of background radiation.

3) The discrete-source model. Ögelman[246] has pointed out that the results of Kraushaar et al. can be explained as γ radiation of galactic x-ray sources if we assume that their energy spectrum is a power law with an exponent $\alpha = 2$. This hypothesis is apparently incorrect. The point is that most galactic x-ray sources have a thermal spectrum which is exponentially cut off at high energies.[247,248] However, it is not excluded that γ-ray sources exist which have a low luminosity in the x-ray region (see, for example, refs. 100 and 249).

Longair and Sunyaev[250] have suggested that the Compton scattering of infrared radiation of the galactic center observed by Frederic and Hoffman[251] and Aumann and Low[252] by relativistic electrons can contribute to the galactic component of diffuse γ rays. Detailed analysis of a similar model, carried out by Maraschi et al.[253,254] has shown that, although γ rays from the radio source Sgr A, which is located in the galactic center, can be detected by contemporary γ telescopes, the total contribution of Compton radiation to the galactic component of diffuse γ rays is comparatively small (see also the work of Stecker et al.[74a]).

Considerable interest is presented by study of galactic γ rays in the soft γ-ray region. The γ-ray intensity in this region can be related to the density of subcosmic rays in the galaxy (this question is discussed in detail by Fowler et al.[255]). Annihilation of low-energy galactic positrons can serve as an additional source of galactic γ rays in the 0.5–2 MeV region. Recently Cline and Hones[256] have reported detection of a rather intense flux of cosmic positrons of low energy ($\lesssim$1 MeV), equal to 10^2 m^{-2}sr^{-1}sec^{-1}MeV^{-1}. The intensity of γ radiation produced in annihilation of these positrons is sufficiently high for separation of the galactic component in the background of isotropic metagalactic γ rays.[257]

C. The Sun

Measurements of the γ-ray intensity of the quiet Sun up to the present time have not yielded positive results. Theoretical estimates of the γ-ray flux from the quiet Sun lead to values lying below the limit of sensitivity of contemporary detectors. Cosmic rays are not produced in the quiet Sun, and three processes are apparently responsible for the production of solar γ rays in this period: 1) interaction of galactic cosmic rays with the solar atmosphere; 2) γ rays from natural radioactive elements (K^{40} and so forth) and 3) γ rays of radioactive nuclei[57] produced in solar flares.

Very great interest is attached to study of solar γ rays at the time of flares. A solar flare is accompanied by production of a large number of electrons and protons (nuclei) of high energy. Interaction of these particles with the solar atmosphere is accompanied by production of intense γ radiation. By studying the properties of this radiation we can obtain information on processes occurring during the flare and on the characteristics of the flare mechanism (density of matter in the vicinity of the flare, preferential direction of emission of solar cosmic rays, and so forth).

The processes for γ-ray production in a flare are extremely diverse. In the energy region 0.1–1 MeV the important processes are electron bremsstrahlung,[258] inverse bremsstrahlung,[59] and annihilation of electrons and positrons. In the region 1–10 MeV an appreciable contribution is made by γ rays from excited nuclei produced in collisions of cosmic rays with matter in the solar atmosphere.[53,259] At higher energies the main role begins to be played by γ rays produced in decay of π^0 mesons formed in nuclear collisions.[260]

According to Elliot's model[261] a flare in γ radiation can precede an optical flare.

Estimates of the fluxes expected depends strongly on the flare models. Details on specific calculations can be found in the articles cited in the preceding paragraph and in the review by Dolan and Fazio.[22] Problems associated with the energetic radiation from solar flares are also discussed in the review by Neupert.[262]

D. Discrete γ-ray Sources

Interpretation of the results of study of γ rays from discrete sources located outside the solar system are rather indefinite. On the one hand, the experimental results are not very numerous and are somewhat con-

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*Shivanandan et al. [239] have reported detection of background radiation in the range 0.4–1.3 mm with an effective temperature of 8°K. If this has a metagalactic origin, then the entire metagalaxy is filled with radiation with an energy density tens of times higher than for the residual radiation. This leads to definite difficulties (for more detail see refs. 241–244). According to recent measurements the effective temperature of the background radiation in this region is 5°K. [245]

tradictory. On the other hand, we know too little about the conditions in potential sources of cosmic γ rays—quasars, radio galaxies, galaxies with increased activity in their nuclei, supernova remnants, pulsars, and so forth. Calculations of the expected fluxes are quite numerous (see, for example, refs. 27—33 and the reviews of Ginzburg and Syrovatskiĭ[6] and Fazio[12,18]) but are quite uncertain; the calculations of different workers frequently differ by an order of magnitude or even more.

Nevertheless the results of study of discrete γ sources present great interest for verification of various hypotheses on the structure of cosmic objects, on the energy sources of the radiation from radio galaxies, quasars, and supernovae, and on the possible existence of unusual objects (neutron stars and so forth). In this section we will discuss several such astrophysical applications of the experimental results of searches for discrete γ-ray sources.

For example, the upper limits on the intensity of discrete sources in the energy region 10^{11}—10^{12} eV[4,130] permit a choice to be made between different models of relativistic electron production in the Crab Nebula and in the radio galaxy M87. Burbidge[263] has proposed that the relative electrons responsible for the radiation of the Crab in the radio-optical and x-ray regions are produced in decay of pions formed in nuclear collisions. However, the upper limit of γ-ray intensity in the range 10^{11}—10^{12} eV is two orders of magnitude below the intensity calculated by Burbidge's model. Consequently, the hypothesis of secondary origin of the electrons in the Crab is not valid, and it is necessary to assume that in the Crab Nebula continuous injection of relative electrons occurs. It is possible that the electron source in the Crab is pulsar NP 0532.[264] Similar calculations have been made also for the outburst in radio galaxy M87,[99,265] in which continuous injection of electrons is also necessary.

Ginzburg and Syrovatskiĭ[266] and Gould[267] have pointed out that in some objects appearance of intense x rays and γ rays is possible in the scattering of relativistic electrons by their own synchrotron radiation. Knowledge of the upper limits of γ radiation permits determination of the lower limit of the average magnetic field in the source (for more detail see refs. 267, 268). In this way lower limits have been obtained for the field in the Crab Nebula ($\bar{H}_{CN} > 4 \times 10^{-5}$ Oe[99]), in pulsar NP 0532 ($\bar{H} > 10^{3}$[269]), the outburst in M87 ($\bar{H}_{D} > 10^{-5}$ Oe[99]), and other sources.[268]

As has been noted previously, measurements of CGR are a powerful instrument for searching for antimatter in cosmic space. The upper limits of γ-ray intensity from quasar 3C 273[99] and a number of sources of infrared radiation[270] refute the hypotheses that annihilation of matter and antimatter serve as an energy source for the radiation of quasars and active galaxies, which have been advanced by Ekspong[271] and Low[272].

Measurements in the soft γ-ray region can serve as a decisive check on the hypothesis of radioactive sources for the energy of supernova explosions.[55,56,273,274] According to these hypotheses the flashes of supernovae should be accompanied by intense γ rays in lines in the energy region 0.4—3.2 MeV.

Continuous monitoring of the sky with detectors with high angular resolution located in satellites will permit verification of a number of suggestions as to the existence of unusual γ-ray sources. Among the potential sources we should mention galaxies with increased activity in their nuclei (for more detail see Burbidge's review[177]). A characteristic feature of these sources is the variability in the radio, infrared, and visible regions.[275,276] Shklovskiĭ[181] has pointed out that explosions in such sources can be accompanied by intense x rays and γ rays. It is not excluded that the excess radiation observed by Volobuev, Gal'per, et al.[176] is none other than the flare of the variable radio galaxy 3C 120 in the γ-ray region.

No less interesting would be the observation of γ rays produced on the accretion of interstellar gas into neutron stars (for more detail see refs. 67 and 278).

According to an estimate by Shvartsman[278] the fluxes expected from neutron stars are 10^{-6}—10^{-7} $\text{cm}^{-2}\text{-sec}^{-1}$, which lies within the range achievable by contemporary γ telescopes.

Very recently Ginzburg and Osernoy[279] have discussed a completely new aspect of the interaction of cosmic γ rays with matter—the change in chemical composition of the material of a source on bombardment by an intense γ-ray flux. They showed that in a number of cases upper limits can be obtained for the intensity of γ-ray sources from optical observations characterizing the chemical composition of the source.

14. PROSPECTS FOR FURTHER STUDY OF CGR

During the first ten years of work in the γ astronomy field a level of $\sim 10^{-4}$ $(\text{cm}^2\text{sec-sr})^{-1}$ has been achieved in measurement of the diffuse flux and $\sim 10^{-5}$ $(\text{cm}^2\text{sec})^{-1}$ in measurement of the flux from a discrete source for γ rays with $E_\gamma \geq 100$ MeV. The next step, as a result of which the level of accuracy of measurement of both fluxes will be raised by another order of magnitude and which can be accomplished in 2—3 years, is in fact already prepared. It consists in use in satellites of spark γ telescopes with a geometrical factor 100—200 cm^2sr, an effective area 100—1000 cm^2, and an angular resolution 2—3°, which have been tested during the last few years in balloons. The first instruments of this type will be the telescope with a wire spark chamber of the Goddard Space Flight Center ($S_{\text{eff}} = 650\ \text{cm}^2$), which is planned to be put into operation in 1971 in the satellite SAS-B (small astronomical satellite)[18,112] and the telescope with a vidicon spark chamber of the Joint European Group ($S_{\text{eff}} = 132\ \text{cm}^2$), which should go into operation in 1972 in the satellite ESRO TD-1.[18,280]

In operation in a satellite the minimum detectable flux of the Goddard Space Flight Center γ telescope is 5×10^{-7} $(\text{cm}^2\text{sec})^{-1}$ under the condition of viewing the entire sky for a period of six months and 1×10^{-7} $(\text{cm}^2\text{sec})^{-1}$ under the condition of tracking a definite discrete source for a period of one week.[268]

At a time when yesterday's balloon γ telescopes are being mounted in a satellite, spark γ telescopes of still larger dimensions are being built for use in balloon flights.[282,283] Thus, for example, the apparatus built by Board et al.[283] uses a 42-gap spark chamber of area 3000 cm^2 with a 35% γ-ray conversion efficiency for $E_\gamma = 100$ MeV and an angular resolution of 1.5°. For eight hours of flight the minimum measurable flux is 5×10^{-7} (cm^{2}sec)$^{-1}$.

There is a real possibility of making further advances and detecting fluxes from discrete sources at a level 10^{-7}—10^{-8} (cm^{2}sec)$^{-1}$. This possibility involves use in a γ telescope of a gas Cerenkov counter operating at low pressure.[18,23] For an effective area $S_{\text{eff}} = 5 \times 10^4$ cm^2 the angular directivity of the telescope will be ±1°. Additional advantages of this type of telescope are its simplicity and low background as a result of suppression of the nonrelativistic particle counting rate. The first apparatus of this type with $S_{\text{eff}} \approx 2 \times 10^3$ cm^2, intended for measurement of γ rays in the energy range 10—100 MeV, should be tested in a balloon flight by 1970.[18,284] A diagram of this device is shown in Fig. 13.[23,284] It was expected, in a six-hour flight, to measure a minimum flux from a discrete source of 5×10^{-7} (cm^{2}sec)$^{-1}$. Then, as in the case with spark γ telescopes, apparatus with gas Cerenkov counters will be used in satellites. Installation of this type of apparatus has been planned in one of the large orbiting scientific stations of NASA.[23] In the tracking mode in a period of one month the minimum detectable flux will be 8×10^{-9} (cm^{2}sec)$^{-1}$.[268]

Further development of γ telescopes will take place not only by increase of the geometrical factor and effective area, but also as the result of improvement in the angular and energy resolutions of the detectors. A promising method in this direction is the combination of a spark chamber with photoemulsion. The spark coordinates indicate the place in the photoemulsion where conversion of a γ ray occurred, and the high spatial resolution of the photoemulsion is utilized to determine the direction and energy of the γ ray. To facilitate the search for the pair in the emulsion, a wide-gap spark chamber is used, which has a higher accuracy in measurement of the coordinates and slope angles of the pair components.[285,289]

The γ telescope with a spark chamber and photoemulsion of Minnesota and St. Louis Universities scheduled for operation in a satellite in 1972 will permit measurement of a minimum flux from a discrete source 5×10^{-8} (cm^{2}sec)$^{-1}$ under tracking conditions.[268]

A substantial increase in the accuracy of energy measurement in γ telescopes can be obtained by using a total-absorption shower counter developed by Hofstadter and Hughes.[286,287] For a γ-ray energy $E_\gamma = 10$ BeV the energy resolution is ~1%. In an apparatus for study of CGR with energy $E_\gamma > 100$ MeV using as an energy-measuring device a total-absorption counter (a cylindrical crystal of NaI(Tl) or CsI(Tl) of diameter 30—40 cm with a height equal to the diameter) and a telescope of multiwire proportional counters to determine the γ-ray angle of arrival, for an angular resolution of about 1° and an energy resolution of 1% or better, it is expected to achieve a geometrical factor of ~540 cm^{2}sr and to reach a limiting measureable diffuse flux as low as 2×10^{-10} (cm^{2}sec-sr)$^{-1}$.[288] The device will be mounted in the High Energy Astronomical Observatory (HEAO), which is planned to be launched in the middle of the 1970's.

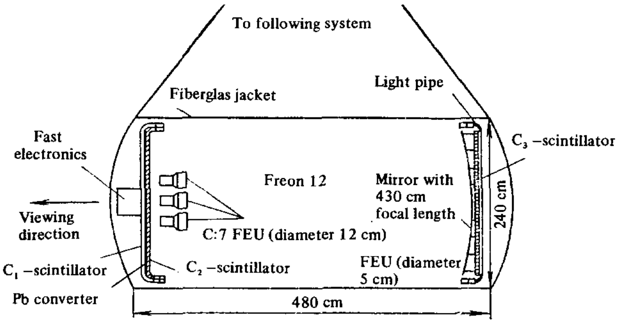

FIG. 13. Diagram of γ telescope with gas Cerenkov counter. [23]

Progress in CGR research depends on improvement of detection methods over the entire range of γ-ray energies. In the soft γ-ray region, substantial improvement of telescopes involves use of germanium-lithium detectors with an active collimator. The angular resolution expected here is ~3°, and the accuracy in energy measurement ~2% for $E_\gamma \approx 1$ MeV.[281]

Two γ-ray energy ranges remain little studied up to this time: the range 5—30 MeV and the range 1—100 BeV, the first because of the low efficiency for γ-ray detection, and the second because of the absence of a suitable method of detection of the low flux which exists at these energies. Special interest is presented by the first unstudied interval, since it can give basic information on the interaction of cosmic rays with gas in the early stages of the expansion of the Universe (see Sec. 13A, p. 645). Apparatus for detection of γ rays in this range has already been built[284,285] and in the near future will be used in experiments.

The range 1—100 BeV will be investigated with the aid of high-aperture γ telescopes.[282-285,288,289] Thus, the γ telescope of Hofstadter and Hughes[288] has a high aperture and detection efficiency, which will permit detection of the γ flux up to energies $E_\gamma \approx 10^3$ BeV.

Future progress in CGR studies will also involve measurements of the polarization of γ radiation, which will permit a deeper understanding of its nature and a separation of the various components of CGR. Apparatus has already been built for measurement of the polarization of x rays,[290] methods for measurement of γ-ray polarization have been proposed,[291] and the first attempts have been made to measure the degree of polarization of the flux of soft x-ray photons.[292-294]

We can hope that most of the γ-ray detectors which have been built or projected will be used successfully in experiments, and that the second ten years of research on γ astronomy will contribute many new important discoveries in this field of study and significantly extend our knowledge of the Universe.

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