Observational gamma astronomy

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A review is presented of the observational data on detection of cosmic γ rays. The importance of observations in γ astronomy in solution of a number of basic problems of cosmic-ray physics, astrophysics, and cosmology (for example, the origin and sources of cosmic rays) is emphasized. Observations of isotropic diffuse and galactic components of γ radiation are presented and analyzed. Methods are discussed for searching for discrete sources of cosmic γ rays, and results are presented on detection of γ-ray fluxes from the sun, the Crab nebula, pulsar NP 0532, Cyg X-3, and other discrete sources. The results of the observations definitely indicate a variability of the discrete γ-ray sources. In conclusion a short review is given of new methods of γ-astronomy observations.

CONTENTS

1. INTRODUCTION

The first attempts to detect extraterrestrial γ rays were made more than ten years ago. For a long time, however it was not possible to measure finite fluxes, and only upper limits of cosmic γ-ray fluxes were determined from the observations.[1-3] This situation arose as the result of the great difficulties in measurement of cosmic γ rays against the background of a large charged-particle flux dominant by several orders of magnitude, and also as the result of the extraordinarily optimistic estimates of fluxes in the first theoretical studies of γ astronomy, which have misled the observers. As a result the creation of observational γ astronomy was delayed, while the "neighboring" x-ray astronomy developed very rapidly. To be fair we must note that even the upper limits of the γ-ray fluxes gave valuable information on processes in the sources and in outer space.[3] Furthermore, during all of this time a constant improvement of the apparatus and methods of observation occurred over the entire range of γ-ray energies, as a result of which the sensitivity of telescopes increased by almost one thousand times.

The situation in γ astronomy has changed substantially during the last two years. Fluxes have been measured of both diffuse radiation and radiation from discrete sources. The progress in γ-astronomy observations is continuing. It is occurring on a broad front, almost identically in the soft γ-ray energy region (0.1–10 MeV), the energetic region (10–1000 MeV), and the ultrahigh energy region (10^2–10^4 GeV). Detectors are obviously approaching finally the necessary level of sensitivity and perfection to become real instruments of observation. Only the hard γ-ray interval (1–100 GeV) has been significantly less studied, as the result of the low fluxes and the lack of high-aperture telescopes. The progress which has been made compels us to acknowledge that observational γ astronomy has already developed and to refer seriously to the first positive results of the observations. Furthermore we can consider that in the rate of collection of new information γ astronomy is no longer inferior to the other divisions of astronomy (even x-ray astronomy), and in the coming years we can expect from it important discoveries. We recall that at the XI International Conference on Cosmic Rays (Budapest, 1969) the results of cosmic γ-ray investigations were included in one rapporteur's talk together with primary electrons and x rays.[4] At the XII Conference (Tasmania, 1971) the abundance of material compelled the organizers to separate cosmic γ rays into a special talk. At the 55th Symposium of the International Astronomical Union (Spain, 1972) there were already two rapporteur's talks: separately on diffuse γ rays[6] and γ rays from discrete sources.[7] In 1973 the results of observational astronomy were discussed already in three international conferences: at the NASA Symposium on γ Astronomy (Greenbelt, April),[119] at the XIII Conference on Cosmic Rays (Denver, August), and at the Conference on Short-duration Fluxes of X Rays and γ Rays (Los Alamos, September).

2. THE IMPORTANCE AND DISTINGUISHING FEATURES OF γ-ASTRONOMY OBSERVATIONS

It is obvious that a correct representation of processes occurring in the Universe can be obtained only by studying it in all regions of the electromagnetic spectrum. It is well known in what processes various forms of radiation arise, and therefore the observational data obtained in different regions supplement each other. In this sense the study of cosmic γ rays is an inseparable part of contemporary astrophysics. However, there is a special feature, belonging to γ radiation alone, which makes these observations extraordinarily valuable for cosmic-ray physics and cosmology.

Gamma radiation is genetically related to cosmic rays: with the electronic component through the processes of bremsstrahlung, synchrotron radiation, and inverse Compton effect, and with the proton-nuclear component through the production and decay of neutral pions.[1)] The latter process contributes only to the γ region, and the main hopes of γ astronomy involve this process. We take this occasion to list the important astrophysical and cosmological problems whose solution depend to a significant degree on the results of observational γ astronomy.

a) Origin of cosmic rays. One of the important problems of contemporary physics is the question of the origin of cosmic rays. Are the cosmic rays observed at the Earth galactic or did they arise somewhat in the metagalaxy and then penetrate into our star system? The discussion of the galactic and metagalactic hypotheses of cosmic-ray origin has been carried on for a long time, but no decisive argument has yet been found. As pointed out by Ginzburg,[8] γ astronomy can provide a definite answer to this question. The protons and nuclei of cosmic rays, colliding with the interstellar gas, produce neutral pions whose decay creates a flux of energetic γ rays with a characteristic spectrum having a maximum at an energy $E = (\frac{1}{2})m_{\pi^0}c^2 = 67.5$ MeV (m_{π^0} is the mass of the neutral pion, c is the velocity of light). If we know the amount of gas in any cosmic object and measure the flux of pionic γ rays from it, we can determine the density of cosmic rays. On the other hand, assuming a certain density of cosmic rays in accordance with some hypothesis as to their origin, we can calculate the expected flux of the γ rays and then compare it with measured values. According to the metagalactic hypothesis the density of cosmic rays at the Earth is the same as everywhere in the metagalaxy and amounts to $\sim 10^{-12}$ erg/cm^3. This cosmic-ray intensity leads to a flux $F(\geq 100 \text{ MeV}) \approx 3 \times 10^{-7}$ (cm^{2}sec)$^{-1}$ from the nearest galaxies—the Magellanic Clouds, whose mass and distance are well known. If the measurements show that the γ radiation from the Magellanic Clouds is much less than this value, this will mean that the density of metagalactic cosmic rays is less than 10^{-12} erg/cm^3, i.e., that the metagalactic hypothesis is invalid. If the flux turns out to be greater, the question remains open, since the greater flux may be due to discrete γ-ray sources in the Magellanic Clouds, and only a detailed study of the γ luminosity of the galaxies will give an unambiguous answer.

b) The activity of the Galactic Nucleus. The problem of the origin of cosmic rays is closely related to the question of the sources of cosmic rays in our Galaxy. One of the possible places where cosmic rays can be produced is the region of the center of the Galaxy, the Galactic Nucleus. The activity of the nucleus in the radio, infrared, and x-ray regions is well known.[9-11] If the activity of the nucleus is due to generation of the cosmic rays, it must be an intense source of pionic γ rays. Observation of γ radiation from the nucleus would be a confirmation of the galactic hypothesis of origin of cosmic rays.[8]

c) Molecular hydrogen. Radio-astronomy observations have revealed the distribution and density of interstellar hydrogen in the Galaxy. These data have been obtained at a wave length of 21 cm and therefore refer to atomic hydrogen. Neither the radio nor the optical observations give an accurate value of the quantity of hydrogen in the form of molecules in the composition of the interstellar gas. Only indirect estimates exist of the amount of molecular hydrogen in dense dust clouds. The most accurate information on the density of hydrogen (in all its forms, and consequently also in the form of molecules) can apparently be obtained from observation of the γ radiation of the Galaxy at the energies of pionic γ rays. Thus, Black and Fazio[42] have indicated regions in the sky from which we can expect increased fluxes of energetic γ rays as the result of the possible content of molecular hydrogen in the composition of dust clouds.

The presence of intergalactic molecular hydrogen can affect the fluxes of the isotropic diffuse γ radiation.[44,65]

d) Formation of galaxies and cosmological γ radiation. The epoch of formation of galaxies in the expanding Universe apparently is also the beginning of the generation of cosmic rays. This time must have left a natural marker in the form of a flux of pionic γ rays which arose as the result of collisions of protons and nuclei of the cosmic rays with the dense matter of the Universe, the so-called cosmological γ radiation.[12] Like its analog, the thermal residual radiation, this flux must be isotropic and at the present time shifted to lower energies as the result of the expansion of the Universe. Thus, the energy at the peak of the spectrum, which is 67.5 MeV at the time of its generation, will become $67.5/(Z_g + 1)$ MeV, where Z_g is the cosmological age of the γ ray or the red-shift parameter corresponding to the galactic formation epoch. According to various assumptions[12,13] $Z_g = 2-100$. Cosmological γ radiation should be observed as some feature, a flattening or an excess, in the energy spectrum of the diffuse isotropic γ radiation. The location of the feature will indicate the parameter Z_g, and the form of the feature can provide information on the density and composition of matter (the hydrogen-helium ratio) at that epoch.

e) The Symmetric Universe and annihilation γ radiation. In a Universe symmetric (or almost symmetric) in matter and antimatter, annihilation γ radiation should arise.[14] In addition to pionic γ rays arising as the result of annihilation of nuclei with antinuclei, a line with energy $E_\gamma = m_e c^2 = 0.51$ MeV from annihilation of positrons with electrons should also arise. The energy of the annihilation γ rays at the present time will be lower by a factor $Z_a + 1$ as the result of the expansion of the Universe, where Z_a is the red-shift parameter of the annihilation epoch. The annihilation γ ray should be isotropic and, like the cosmological γ rays, can appear in the form of some feature in the spectrum of diffuse γ radiation.

Because of the absorption of γ rays in the dense matter of the expanding Universe the annihilation and cosmological radiation can reach the present time only from times $Z \leq 100$.

f) Metagalactic cosmic rays. Study of diffuse x rays and γ rays provides information on metagalactic cosmic rays. While the electronic component produces radiation in the x-ray and γ-ray regions (mainly through inverse Compton scattering by residual photons), the proton-nuclear component will contribute only to the γ rays, as the result of collisions with metagalactic gas and the production and decay of neutral pions.

Thus, the energy spectrum of the diffuse isotropic x and γ radiation includes information on the composition, the spectrum, and intensity of metagalactic cosmic rays and on the time of origin and evolution of the sources.[26]

The problems enumerated of course do not exhaust the main problems of γ astronomy. At the present day they are the most interesting, since they can be solved in the near future. An important problem, for example, is the search for discrete γ-ray sources whose production mechanism may be either pionic, synchrotron, bremsstrahlung, or Compton. In particular, as indicated by Pinkau,[122] the expanding clouds of supernovae, which contain cosmic rays, will be recorded as extended discrete sources of γ rays whose angular dimensions may be as large as several degrees. The study of γ rays from such peculiar objects as pulsars, supernova clouds, x-ray sources, and assumed black holes is very promising. It is clear that the nature of these unusual objects can be unmasked only with the use of γ-astronomy data.

Of particular interest is the observation of γ rays from galactic nuclei and quasars, in particular, in the light of Ambartsumyan's idea[15,16] of a "new physics" existing in these objects, which consist, it is supposed, of superdense prestellar matter. The processes occurring in them are distinguished by a large energy release, and the γ radiation, which is the most energetic in the electromagnetic spectrum, will be able to reveal for the first time the existence of such forms of matter. In this case the data of γ-astronomy observations will make possible progress far beyond the realm of astrophysics.

3. ISOTROPIC DIFFUSE γ RADIATION

The isotropic component of diffuse γ radiation is identified with radiation of the metagalaxy, and its study is of the first importance for astrophysics and cosmology (see Secs. d–f of Part 2).

The experimental situation with isotropic diffuse radiation is characterized not only by the obtaining of new data, but also by the correction of errors made in earlier studies. In order to understand better the changes which have occurred, we will consider the energy spectrum of isotropic diffuse γ radiation, which was discussed two years ago at the XII Conference on Cosmic Ray Physics, Tasmania. The results of the measurements are shown in Fig. 1. The greatest number of studies have been made in the soft γ-ray region.[17-19] Data on energetic γ rays were obtained only in two measurements made in the satellites OSO-3[20,21] and Cosmos 208[22]. The spectrum reported had the following features: a) A break in the spectrum at an energy of ~40 keV (the data of Schwartz et al. obtained in OSO-3[17]). b) A flattening of the spectrum, beginning at an energy $E_\gamma \approx 1$ MeV and above (the data of Vette et al.[23] obtained in the extended-orbit satellite ERS-18, which goes beyond the magnetosphere). Vette's data, however, were in disagreement with the results of Golenetsky et al.,[24,25] which were obtained in the satellites Cosmos 135 and 163 with an orbit close to the Earth. c) The absence of accurate data (only upper limits were given) for energetic γ rays. In the energy interval from 6 to 30 MeV no experiments have been performed. The features in the spectrum of diffuse radiation have been the starting point of many theoretical hypotheses. An attempt has been made to explain the break in the spectrum at 40 keV by a change in the spectrum of metagalactic electrons. The flattening of the spectrum in the interval 1–6 MeV has been treated as the contribution of cosmological γ rays.

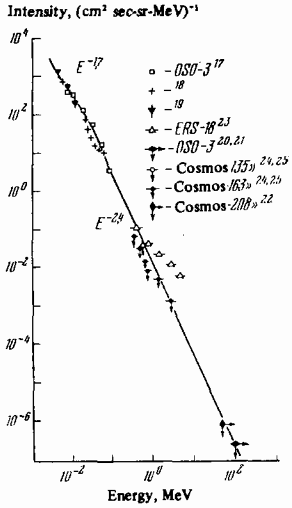


FIG. 1. Differential energy spectrum of diffuse γ radiation, measured up to 1971.

The events of the last two years have substantially changed the situation. Experimental results have appeared in the previously unstudied interval, and the incorrectness of the conclusions regarding the features in the diffuse radiation spectrum has been demonstrated. Where did the errors of the earlier studies lie? It has been shown that in the soft γ-ray interval the detected fluxes receive a substantial contribution from the induced activity, artificial radioactivity, of the detector material induced by cosmic rays. One of the causes of appearance of the large γ-ray flux measured in ERS-18 and which led to a flattening of the spectrum is just the induced activity, as was shown in refs. 24, 25, and 28. It was also demonstrated that the traditional means of determining the flux of cosmic γ rays in measurements in high-altitude balloons, by linear extrapolation of data obtained by omnidirectional detectors to the edge of the atmosphere, is incorrect. A number of authors[6,27,28] have shown experimentally and theoretically that near the edge of the atmosphere (for depths $\lesssim 10$ g/cm^2) the flux of secondary γ rays not only does not fall linearly with decreasing depth, on which the linear extrapolation was based, but even increases, imitating the primary flux. A particularly detailed analysis of this slope effect has been made by Danjo.[6,29]

Thus, the situation has been clarified to a substantial degree. Figure 2 shows the measurements of the isotropic diffuse flux obtained up to the present time. The break at 40 keV has disappeared, and there is no

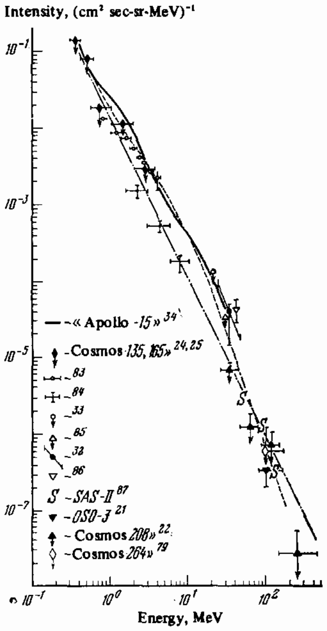


FIG. 2. Differential energy spectrum of diffuse γ radiation according to measurements in September 1973. The dot-dash line is an extrapolation from the x-ray region (~E$^{-2.1}$); the dashed curve is a calculation according to the Brecher-Morrison model (Compton scattering of electrons by the three-degree radiation [30]) with addition of cosmological γ rays with Z = 100 (ref. 14).

flattening of the spectrum in the interval 1—10 meV. The experimental results from 20 keV to 1 MeV can be represented by a single power spectrum[6]:

$$\frac{dI}{dE}=25\cdot 10^3\left(\frac{E}{\text{keV}}\right)^{-2,1}\text{photons}\times(\text{cm}^2\text{-sec-sr-MeV})^{-1}. \tag{1}$$

This empirical dependence is in good agreement with the theoretical spectrum of diffuse γ radiation arising in Compton scattering, by the three-degree residual radiation, of relativistic electrons produced in radio galaxies and filling metagalactic space.[30,31] Inverse Compton scattering is apparently the main process which determines the shape of the diffuse radiation spectrum in the energy region up to 1 MeV. The deviations from the theoretical spectrum are small and may be due to the contribution of discrete metagalactic sources. The spectrum (1), extrapolated to the high-energy region, can serve as a guide for measurements of γ rays with energy 1—100 MeV.

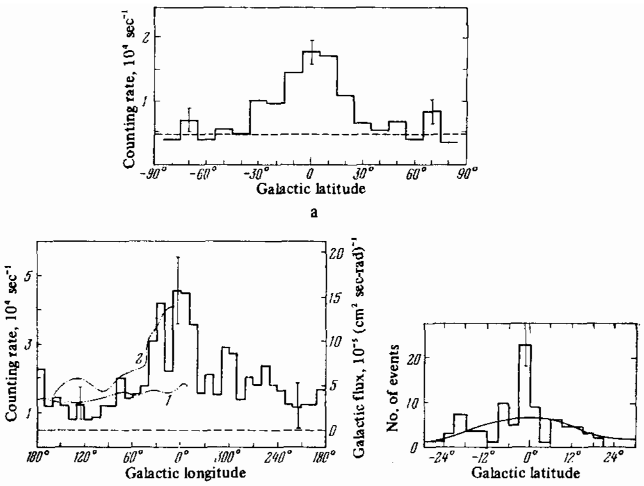
Recently a number of such measurements have been carried out. The observations were made by various methods: a large omnidirectional γ detector on the space ship Apollo-15 during its flight from the Moon to the Earth,[34] a high-aperture γ telescope with wire spark chambers operating for an extended period in the small astronomical satellite SAS-II,[87] and also γ telescopes taken up in baloons. Spark chambers[32,33,85,86] were used for the first time in balloon observations in the energy region $E\gamma \leq 50$ MeV, and in the interval 1—10 MeV the method of detecting γ rays by means of double Compton scattering has been used.[66,84] Both methods substantially increase the reliability of identification of the γ rays.

From the results of the observations it follows that a) in the interval 1—50 MeV some excess of the measured flux over the extrapolated spectrum (1) is observed; b) in the interval 50—250 MeV the spectrum becomes steeper and is characterized by an exponent ≈ 3,[87] which also is inconsistent with the extrapolation of Eq. (1).

Figure 2 also shows a theoretical spectrum which takes into account, in addition to the dominant process of Compton scattering of metagalactic electrons by thermal residual photons,[30] a cosmological flux with a red shift $Z = 100$. Most of the experimental results, including those obtained in Apollo and SAS-II (which are statistically more reliable and cover a wider energy range) are in good agreement with the theoretical spectrum, which suggests the existence of cosmological γ radiation (see sections d and f of Part 2). However, the results of refs. 22, 25, and 84, which do not find excesses, and of ref. 33 which notes the possibility of explaining the excess by an instrumental background, do not permit the observation of cosmological radiation to be considered as finally established. Additional experiments are necessary.

4. GALACTIC γ RADIATION

The greatest number of results have been obtained in study of γ radiation from the Galaxy (Milky Way). By 1967 Clark, Garmire, and Kraushaar in the orbiting solar observatory OSO-3 had measured a γ-ray flux with energy $E\gamma \geq 100$ MeV coming from the Galactic plane.[20] Analysis of the experimental data occupied several years, and the final data appeared only in 1972.[21] Figures 3a and b show the distributions of the flux as a function of galactic latitude b'' (after subtraction of the region of the Galactic Center $|l''| \leq 30$) and the galactic longitude l''. The measured flux is represented in the form of the radiation of a linear source whose intensity is $(1.3 \pm 0.3)\times 10^{-4}$ photons $(\text{cm}^2\text{sec-rad})^{-1}$ from the region of the Galactic Center $(-15^\circ < b'' < 15^\circ,\ -30^\circ < l'' < 30^\circ)$ and $(3.4 \pm 1.0)\times 10^{-5}$ photons $(\text{cm}^2\text{sec-rad})^{-1}$ on the average for other parts of the Galaxy $(-15^\circ < b'' < 15^\circ,\ 30 < l'' < 330^\circ)$.[21]



a

b

c

FIG. 3. Galactic γ radiation. Latitude and longitude distribution according to the data[20,21] of OSO-3, $E_\gamma \geq 100$ MeV (a, b) and (ref. 67) $E_\gamma \geqslant 15$ MeV (c). The dashed line shows the level of the isotropic diffuse flux for latitudes $||b''|| \geqslant 35^\circ$; curves 1 and 2 are theoretical calculations respectively by Cavallo and Gould[43] and Strong et al.[26]. The solid line in Fig. 3c is the background of atmospheric γ rays.

The interpretation of the OSO-3 results as the radiation of a linear source located along the Galactic equator was based on the latitude distribution shown in Fig. 3a. The width of the peak, which amounts to ~30°, is completely explained by the poor angular resolution of the detector (±15°). Recent observations made by γ telescopes with better angular resolution (using spark chambers and emulsions) have confirmed the correctness of this representation.[67,87] Figure 3c shows the latitude distribution of γ rays with energy $E\gamma \geq 15$ MeV measured by means of emulsion.[67] The width of the peak has narrowed to 3° and as before is determined by the angular resolution of the detector.

The distribution of γ rays as a function of Galactic longitude (Fig. 3b) reveals a broad maximum located along the equator in both directions from the center. According to the SAS-II data[87], the width of the maximum is ~70°.

Comparison of the results of different studies of the flux of galactic γ rays permits the first suggestions to be made as to the energy spectrum (Fig. 4).

The experimental results rule out both a pure power spectrum and (less definitely) a pure pionic spectrum and agree with a combined spectrum in which for energies $E\gamma \geq 70$ MeV the pionic component dominates, and in the region $E\gamma < 70$ MeV there is a significant addition with a softer power spectrum.

The theoretical discussion of the measured galactic γ radiation is based on the fact that the main part of the galactic flux is made up of pionic γ rays produced in collisions of the nuclear-active component of cosmic

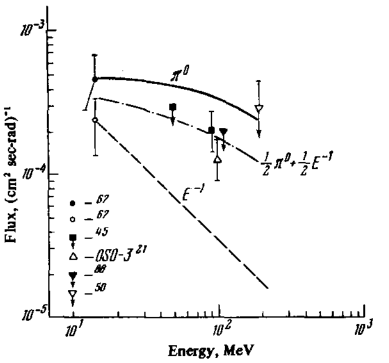


FIG. 4. Integral energy spectrum of γ rays from the region of the Galactic center. The curves show spectra for pure pionic, pure power, and mixed fluxes. Since the γ-ray detection efficiency depends on the shape of the spectrum (particularly for low energies), the data of ref. 67 are designated by a solid circle for a pionic spectrum and a hollow circle for a power spectrum.

rays with interstellar gas. Calculations made by Cavallo and Gould[43] and Stecker[44,69] on the assumption that the cosmic-ray flux over the entire galactic disk is the same as that measured near the Earth (with solar modulation taken into account) have shown the agreement of the theoretical intensity of galactic γ radiation with the measured values everywhere except in the region of the broad peak near the Galactic center.

Figure 3b, curve 1, shows the theoretical calculation of Cavallo and Gould. The measured flux from the region of the Galactic center is approximately three times the theoretical flux, which provided a basis for assumption of other additional sources of galactic γ rays, for example, as the result of Compton scattering of relativistic electrons by the infrared radiation,[70,72,73] which still did not remove the discrepancy. A more productive idea is that of Strong et al.[86] who suggested that the cosmic-ray intensities in different regions of the Galaxy are different and are proportional to the magnetic fields in these regions. This is a natural idea, since in large fields charged cosmic rays are retained longer and can therefore accumulate. A convenient analogy is the region of captured radiation in the magnetic field of the Earth. Curve 2 in Fig. 3b shows that the longitude dependence of the theoretical intensity in this case is in good agreement with the observational data. Similar reasoning regarding the increased intensity of cosmic rays near the galactic center has been given by Anand and Stephens.[74]

The experiments carried out have demonstrated with a high reliability that there is galactic γ radiation and, as often happens in such cases, have raised still more questions. Much is still unclear both in comparison of the results of different observations and in their astrophysical decoding. For example, what is the soft power component in the spectrum of the flux from the galactic center? What is indicated by the increased intensity of cosmic rays in the region of the galactic center? It is possible that it indicates generation of cosmic rays by the Galactic nucleus, as suggested by Ginzburg,[81] although in this case a discrete γ-ray source should be observed in the galactic center (see section b, Part 2).

At the present time the question of the existence of a discrete source in the galactic center has not been finally solved. The poor angular resolution of the detectors of Clark et al.[21] and Helmken et al.[46] did not permit a central source to be identified. If there is such a source, its intensity is $(4.9 \pm 1.8) \times 10^{-5}$ photons/cm^2-sec for energies $E\gamma \geq 100$ MeV[21] and $(1.9 \pm 0.7) \times 10^{-4}$ photons/cm^2-sec for $E\gamma \geq 15$ MeV.[46] Observation of the region of the galactic center by means of telescopes with angular resolution ($\sim 2-3°$) gave no unique result. Thus, Frye et al.[38] found a discrete source located near the center, from which the flux was $(1.5 \pm 0.5) \times 10^{-5}$ photons/cm^2-sec for energies $E\gamma \geq 100$ MeV. Fichtel et al.[45] did not observe a central discrete source, although their observations were made with a similar apparatus. Kinzer et al.[67] give for the central source an upper limit 6×10^{-5} photons/cm^2-sec for $E\gamma \geq 15$ MeV.

Preliminary results of observations in SAS-II also have not revealed a central source.[80]

5. DISCRETE SOURCES OF γ RAYS

Many experimental studies have been devoted to the question of discrete γ-ray sources. Most of these studies have been carried out in high-altitude balloons. In comparison with satellites, balloon observations are less reliable and informative, since they are carried out against a high background of atmospheric γ rays, are of short duration (hours), and permit only individual portions of the sky to be scanned. The balloon observations of the last two years are separated into two groups on the basis of the results obtained: one group[45-47,49,50,67] finds only diffuse radiation from the galactic disk and confirms the intensity of the linear source measured in OSO-3, and the other group[38,48,51-53,58] reveals a whole series of discrete γ-ray sources, from whose fluxes almost the entire galactic radiation is made up. Sources have also been found away from the galactic equator.[51,52,58]

It appears to us that the reliability of some of the reported sources is inadequate and that additional observations are required to confirm them. For this reason the representation of the galactic γ radiation as consisting of individual discrete sources is not at all justified. The methods of identifying the discrete sources observed in refs. 48, 51, 53, and 58 has been criticized by O-Mongain[77], who pointed out the inadequate consideration of the possibility of grouping of γ rays as the result of random fluctuations.

In this connection it is natural to raise the question of the reliability of detection and the criteria of discovery of a discrete source. The degree of reliability is a relative concept, and various approaches are possible to the development of criteria for the acceptance of a source. For example, in the observations in the satellite SAS-A (Uhuru)[75] a discrete source of x rays was considered reliably established if the excess over background exceeded 3.4 σ_{eff} in one scanning and 2.4 σ_{eff} in each of two scannings of the region of the excess, where σ_{eff} is the effective standard deviation. Hearn[76] and O'Mongain[77] proposed a maximum likelihood function method for determination of criteria for acceptance of a source and also for calculation of the fluxes, their errors, and upper limits.

The likelihood function for observation of a source for the case of a Poisson distribution of the background events is of the form

$$L(S) = \frac{1}{M}\left(\frac{S}{B}+1\right)^N e^{-S}, \qquad (2)$$

where N is the number of γ events observed from some portion of the sky, B and S are the number of background events and events from the source from this same portion, and M is the number of samples (subdivisions, displacements) used in analysis of the experimental data. The maximum value $L_{\max}$ of the function is reached for $S_{\max} = N - B$. The criterion for observation of a source is taken as the 95% confidence level ($C = 0.95$) for which

$$L_{\max} \geqslant \frac{1}{1-C_1} = 20. \tag{3}$$

The errors S_+ and S_- and the upper limit S_{up} of the flux from the source are determined from the expressions

$$L(S_\pm) = e^{-0.5} L_{\max}(S_{\max}), \tag{4}$$

$$L(S_{\text{up}}) = L_{\max}(S_{\max})(1 - C). \tag{5}$$

However, the most convincing proof of existence of a discrete source is the detection of the excess flux from it not only in two observations of the same group but also in different groups (the criterion of repeatability). The fact of repeated observation can be taken into account in the method of maximum likelihood as a reduction in the samples from whose number an event with an excess is found.

We will consider in more detail the data on detection of γ rays from several of the most reliable discrete sources.

a) γ radiation from the Sun. No γ radiation from the quiet Sun has yet been observed. The upper limits of the fluxes, both in the soft γ-ray interval and to a greater degree in the energetic range, are still too large and 2--3 orders of magnitude greater than the expected solar γ-albedo flux arising as the result of cosmic rays. The level of the Sun's γ radiation increases significantly during chromospheric flares, as was shown by the observations of Chupp et al.[82] in the orbiting solar observatory OSO-7. The observations were made with a crystal of NaI(Tl) of area 7 × 7 cm surrounded by an anticoincidence screen of CsI(Na). The energy of photons in the interval 0.3–10 MeV was measured from the scintillation pulse height in the crystal by means of a multichannel pulse-height analyzer. The resolution of the equipment was ~8% for the 662-keV line. During the entire flight a calibration was carried out with a Co^{60} source. Gamma-ray line spectra were recorded during two flares in August, 1972. The measured γ fluxes are given in Table I.

The duration of the bursts of γ rays was several minutes. In the observations of August 4, two stages of the flare were followed; the measurements of August 7, which began after the satellite left the shadow, missed the initial phase of the flare. In the August 4 flare an increase in counting rate was observed in four channels, indicating detection by the apparatus of a γ-ray line spectrum from the Sun with energies of 0.5, 2.2, 4.4, and 6.1 MeV. The first two lines are well known. They arise in annihilation of a positron and electron at rest:

$$e^+ + e^- \to 2\gamma, \quad E_{\gamma_1} = 0.51\,\text{MeV}, \tag{6}$$

and in capture of a neutron by a proton with formation of a deuteron:

$$n + p \to d + \gamma, \quad E_{\gamma_2} = 2.23\,\text{MeV}. \tag{7}$$

TABLE I. Fluxes of γ-ray lines from the Sun during chromospheric flares. [82]

Flare, time of measurement	Flu, photons(cm² sec)⁻¹			
	0.5 MeV	2.2 MeV	4.4 MeV	6.1 MeV
2B(H_α), 2 August 1972, 0626–0632 UT (before maximum H_α)	$(7\pm1.5)\cdot10^{-2}$	$(2.2\pm0.2)\cdot10^{-1}$	$(3\pm1)\cdot10^{-2}$	$(3\pm1)\cdot10^{-2}$
3B(H_α), 7 August 1972, 1538–1547 UT (after maximum H_α)	$(3.7\pm0.9)\cdot10^{-2}$	$(2.6\pm1)\cdot10^{-2}$	$<2\cdot10^{-2}$	$<2\cdot10^{-2}$

The interpretation of the other two lines is less definite. They may be due to radiation of excited C^{12*} nuclei ($E\gamma_3 = 4.43$ MeV) and O^{16*} nuclei ($E\gamma_4 = 6.13$ MeV). Detection of γ-ray lines from the Sun provides interesting information on processes occurring during a flare and involving acceleration of particles. The 2.2-MeV line definitely indicates the appearance of a neutron flux in the solar atmosphere, and the annihilation line indicates the production of a large number of π mesons which lead to appearance of a positron flux through the decay chain $\pi \to \mu \to e$. The number of protons accelerated in the flare was determined from the intensity of the nuclear lines. During the flare duration of $\sim10^3$ sec 2×10^{33} protons were formed with energies 10–50 MeV. Important information is also provided by the time dependence of the γ rays. Figure 5 shows the time variation of the counting rate of solar γ rays with energy 0.5 and 2.2 MeV and of hard x rays. As can be seen, during the flare the x-ray and γ-ray fluxes increase simultaneously and synchronously. The rise of the γ radiation to its maximum value, which characterizes the time of acceleration of solar protons, occurs in a period of less than ten minutes.

b) γ radiation of the Crab Nebula and pulsar NP 0532. It is well known that the Crab Nebula, which was formed by the expanding shell of the Supernova of 1054, is observed in all regions of the electromagnetic spectrum from radio frequencies to hard x rays. In addition, radio, optical, and x-ray radiations pulsating with a period of ~33 msec have been observed from the pulsar NP 0532, which is located in the center of the Crab Nebula and is a neutron star—a Supernova remnant.

Radiation of the Crab Nebula and pulsar have also been measured in the γ region in many studies, mostly carried out very recently. Observation of the pulsating component has been particularly successful. As an example we have shown in Fig. 6 the detection of a pulsating radiation with energy 0.1–0.4 MeV.[59] The pulsations appear distinctly if a time analysis of the γ-ray counting rate is made on the basis of the accurate

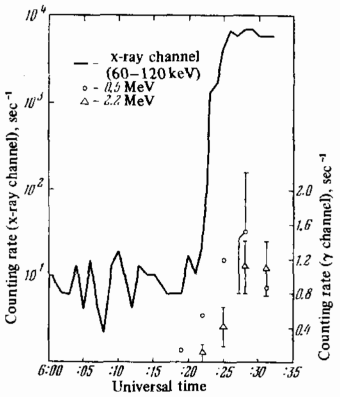


FIG. 5. Detection of solar x rays and γ rays at the time of the class 2B burst of August 4, 1972 (ref. 82).

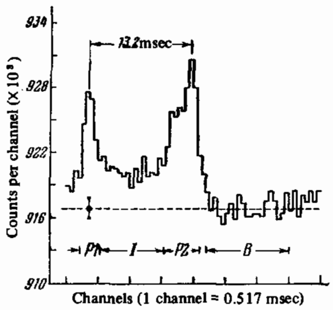


FIG. 6. Measurement of pulsating γ radiation with energy 0.1–0.4 MeV from pulsar NP 0532 (ref. 59). P1 is the main pulse, P2 is the second pulse, I is the radiation between the pulses, and B is the background.

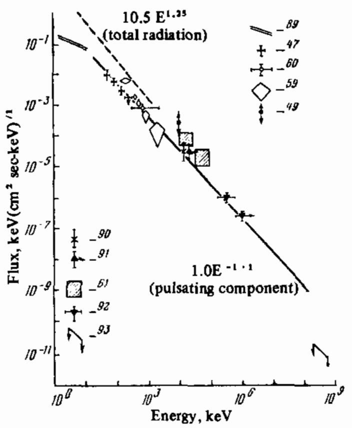


FIG. 7. Energy spectrum of γ rays from pulsar NP 0532. The solid line shows the best approximation of the experimental data ($E^{-1.1}$); the dashed line shows the total radiation of the Crab Nebula.

period obtained from radio observations during the same time interval. It is possible to identify clearly the main pulse (P1), and a second pulse (P2) spaced 13.2 msec from the first, in agreement with observations in the radio, optical, and x-ray regions, as well as an increased intensity between the pulses. The dashed line shows the background produced by atmospheric γ rays and charged particles. Although the contribution of the pulsating component to the total counting rate of the apparatus amounts to only 0.7%, the time analysis permits it to be reliably separated. In other studies in which the pulsating γ radiation of NP 0532 has been measured in the interval 0.1–1000 MeV, the main and second pulses have also been observed with amplitudes of 2.6 to 5 standard deviations above the background.[39,41,49,60-62,90-92]

The time sequence of the pulses is not substantially different from that observed in the radio, optical, and x-ray regions. Thus, the location of the main pulse in all γ-ray intervals agrees within 0.5 msec with the location in the other regions of the electromagnetic spectrum. However, the structure of the pulsating radiation undergoes significant variations as the γ-ray energy increases: in the x-ray region the second pulse is larger than the main pulse (a ratio of 2.3), while in the energetic γ-ray interval ($E\gamma \approx 20$ MeV) in the best case they are comparable (the ratio becomes no greater than 1.2).[61,91]

The radiation spectrum of NP 0532 is shown in Fig. 7.[90] The observational data are best approximated by a power law

$$\frac{d(EI)}{dE} = 1.0E^{-1.1}\ \mathrm{keV}\,(\mathrm{cm}^2\mathrm{sec\text{-}keV})^{-1} \qquad (8)$$

The dashed line shows the spectrum of the total (pulsating and constant) radiation of the Crab Nebula, which can be represented in the form[90]

$$\frac{d(EI)}{dE} = 10.5\,E^{-1.25}\ \mathrm{keV}\ (\mathrm{cm}^2\mathrm{sec\text{-}keV})^{-1} \qquad (9)$$

The spectrum (8) is flatter than (9), which leads to an increase in the fraction of the pulsating component with increasing energy. It amounts to 2–10% in the x-ray region and more than 20% in the γ-ray region ($E\gamma \approx 1$–10 MeV). Extrapolation of the spectra (8) and (9) to the higher-energy region leads to their merging at an energy of several GeV, which would indicate an increase of the fraction of the pulsating component to 100% at these energies.

The results of measurements by Hillier et al.[41] and Kinzer et al.[40,49] give large fluxes of the pulsating component which exceed the spectrum (8), which may indicate time-varying flares in which the fraction of the pulsating component increased almost to 100% in the soft γ-ray interval.

The γ radiation of the Crab Nebula has been measured also in the ultrahard radiation region. As the result of two-year observations of the Crab Nebula by the surface Cerenkov telescope of the Smithsonian Observatory a flux was measured, averaged over the entire time of observation, whose magnitude is $F\gamma(\geq 2.5 \times 10^{11}\ \mathrm{eV}) = (4.4 \pm 1.4) \times 10^{-11}$ photons $(\mathrm{cm}^2\mathrm{sec})^{-1}$ (ref. 64). Time analysis of these same data with the period ~33 msec did not reveal a pulsating component of the ultrahard radiation of the pulsar.[93] The upper limit of the flux, shown in Fig. 7, is 100 times less than the extrapolation according to the spectrum (8), which indicates a change in the slope of the spectrum in the interval 1–100 GeV. The fraction of the pulsating component determined from the upper limit does not exceed 30% (ref. 94). However, Grindlay[83,117] and Grindlay et al.[81] have indicated the existence of a pulsating flux of intensity $F\gamma(\geq 5 \times 10^{11}\ \mathrm{eV}) = (7.5 \pm 4) \times 10^{-12}$ photons $(\mathrm{cm}^2\mathrm{sec})^{-1}$.

Fazio et al.[64] have observed also a flux variation correlated with the times of spontaneous changes in the period of pulsation of NP 0532. For three changes in the period which occurred in 1969–1971 an increase in flux to a value $(1.21 \pm 0.24) \times 10^{-10}$ photons $(\mathrm{cm}^2\mathrm{sec})^{-1}$ was observed in the time interval from 60 to 120 days after the change in period. Since just this period is required for a relativistic particle to cross the Crab Nebula, we can assume that the recorded bursts of ultrahard γ rays represent radiation of the entire Crab Nebula induced by a flux of particles emitted by the pulsar. The total energy of the radiation was $\sim 10^{41}$ ergs, approximately equal to the energy released in the change in angular momentum of the pulsar.

The mechanism of the radiation of the Crab Nebula and pulsar NP 0532 over all regions of the electromagnetic spectrum studied up to 100-MeV γ rays is synchrotron radiation of relativistic particles with energy up to 10^{17} eV moving in magnetic fields. For energies greater than 100 MeV the dominant mechanism becomes Compton-synchrotron,[5,95] in which the photons of synchrotron radiation produced by the electrons undergoes Compton scattering by other relativistic electrons and are converted to high-energy γ rays. The two mechanisms permit estimation of the average magnetic-field strength in the Crab Nebula ($\overline{H}_{CN}$) and in the pulsar ($\overline{H}_p$). From data on the ultrahard γ radiation it was found that the transverse component of the magnetic field of the Crab Nebula is $\overline{H}_{\perp CN} = 2.5 \times 10^{-4}$ G on the assumption of a uniform field and $\overline{H}_{\perp CN}(0) = 10^{-3}$ G for the value of the field in the center with a 1/r law of variation.[94,95] Estimation of the pulsar magnetic field[121] gives a value $\overline{H}_p > 10^3$ G.

c) Other discrete γ-ray sources. One of the regions of the sky from which excess γ-ray fluxes have been recorded is the Cygnus constellation. The region of the sky in the Cygnus constellation has been studied as often as the regions of the Galactic center and the anticenter with the nearby Crab Nebula. The Cygnus constellation is convenient for balloon observations, since it is seen in ascents at medium latitudes in the northern hemisphere, where the main ascent areas of Europe and America are located. Figure 8 shows a schematic map of the region of Cygnus with the sections from which excess γ-ray fluxes have been observed. The boundaries of these sections indicate the possible location of the source determined by the inaccuracy in measurement of the direction of arrival of the γ rays, within one standard deviation. The results of the observations are given in Table II. A flux of γ rays with energy $E_\gamma \geq 50$ MeV above the atmospheric background was recorded for the first time in 1965 by Duthie et al.[35,100] by means of a spark-chamber γ telescope. The flux was $F_\gamma(\geq 50\text{ MeV}) = (1.8 \pm 0.6) \times 10^{-4}$ photons $(\text{cm}^2\text{sec})^{-1}$ (ref. 100). However, in the two observations of Frye et al.[101] carried out before and after Duthie's observations[35] with an interval of about nine months, no excess was observed. Subsequently, excess radiation with γ-ray energy about 100 and 60 MeV was again recorded from this region.[57,97,96,120] In 1970 the group at the Crimean Astrophysical Observatory, in recording ultrahard γ rays by means of the Cerenkov radiation of showers, observed an excess flux $F_\gamma(\geq 2 \times 10^{12}\text{ eV}) \approx 2 \times 10^{-11}$ photons $(\text{cm}^2\text{sec})^{-1}$ from this same part of the sky.[54] The excess over the atmospheric background amounted to 3.6 standard deviations. The observations carried out by this same group in 1971 revealed no excess, and the upper limit of the flux was five times less than that measured previously.[55] As can be seen, the situation is rather complicated; however, on the basis of the statistical estimates and the reproducibility of the observations of excess fluxes we must acknowledge the existence of a discrete γ-ray source whose location is determined by the coordinates: right ascension $\alpha = 304° \pm 1.0°$, declination $\delta = 35.5° \pm 1.0°$ (the source KRAO-1).[54,102] The absence of the source in some investigations can be explained by its variability, as a result of which the flux turned out to be below the level of sensitivity of the telescopes. In this case it follows from the observations that in the course of 6–9 months the flux changed by about an order of magnitude in the energy interval $E_\gamma \geq 100$ MeV and at least by a factor of five in the ultrahard γ-ray region.

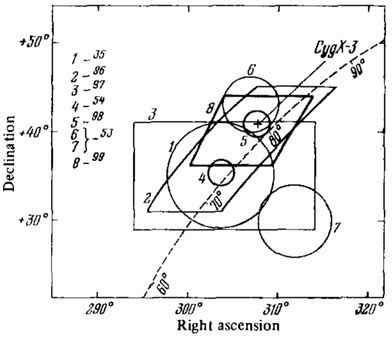


FIG. 8. Map of the region of the constellation Swan. Regions of excess γ radiation are shown. The dashed curve shows the Galactic equator.

TABLE II. Excess γ-ray fluxes from the region of the Swan constellation.

Region in Fig. 8	Authors	Date	Threshold energy, MeV	Flux $F_\gamma(>E)$, photons $(\text{cm}^2\text{ sec})^{-1}$	Excess over background, in standard deviations
1	Duthie et al. [35,100]	23.10.1965	50	$(1.8 \pm 0.6)\cdot 10^{-4}$	3
	Frye and Wang[35,100]	01.1965 07.1966	100 100	$< 6\cdot 10^{-5}$ $< 1.2\cdot 10^{-5}$	
2	Valdez and Waddington[96]	07.1967	100	$(3 \pm 1.5)\cdot 10^{-4}$ rad^{-1}	4
	Hutchinson et al.[120]	04.1968–06.1968	40	$(4.9 \pm 2,1)\cdot 10^{-4}$ rad^{-1}	2.6
3	Niel et al.[97]	9.10.1969 16.10.1969	60	$(5.7 \pm 3)\cdot 10^{-5}$	1.8
4	Vladimirskiĭ et al.[54]	08.1970–10.1970	$2.5\cdot 10^6$	$2\cdot 10^{-11}$	3.7
	Vladimirskiĭ et al. [55]	1971	$2.5\cdot 10^6$	$< 4\cdot 10^{-12}$	

The search for γ rays from the discrete source Cyg X-3 located in the Cygnus constellation had a mission-oriented nature. From this source several intense bursts of radio and infrared radiation[103,104] were recorded during September and October, 1972. The location of the source of the burst was defined by radio-observational data as having coordinates $\alpha_b = 307°39'$, $\delta_b = 40°47'$, and the distance to it was estimated as about 12 kpc.[104] The x rays from Cyg X-3 during this time did not have the nature of a burst, but were observed to have a sinusoidal variation with a period of 4.8 hours and a smooth drift of both the average level and the amplitude of the oscillations.[105] The source Cyg X-3 is apparently a double system.

Vladimirsky et al.[98], who used a surface γ telescope to observe the source Cyg X-3 for several days after the first burst of radio radiation, recorded a flux of ultrahard γ rays exceeding the background by 5σ: $F_{\text{Cyg X-3}}(\geq 10^6\text{ MeV}) = 2 \times 10^{-10}$ photons $(\text{cm}^2\text{sec})^{-1}$. Gal'per et al.[99] observed the region of the Cygnus constellation with a wide-angle telescope with spark chambers in a high-altitude balloon for several days after the second burst of the source. From the part of the sky in whose center Cyg X-3 is located an excess flux exceeding background by 3.6σ was observed $F_{\text{Cyg X-3}}(\geq 40\text{ MeV}) \approx 2 \times 10^{-4}$ photons $(\text{cm}^2\text{sec})^{-1}$. The results reported indicate with a higher degree of reliability the existence of γ rays from the flashing source Cyg X-3 during the period of its increased activity. The intensity of γ radiation from Cyg X-3 amounted to $\sim 5 \times 10^{37}$ erg/sec for energies $E_\gamma \geq 40$ MeV and $\sim 2 \times 10^{36}$ erg/sec for $E_\gamma \geq 10^{12}$ eV. At the same time the x-ray intensity for energies 2–6 keV was $\sim 6 \times 10^{37}$ erg/sec.

We will consider two additional discrete sources of γ rays with energy greater than 100 MeV: Lib γ-1 (ref. 52) and Tau γ-1 (ref. 37), which were tentatively identified with the extragalactic radio objects PKS 1514-24 and 3C 120. The source Lib γ-1 was recorded in one observation, in which the excess γ-ray flux exceeded the background by 6σ. Since no excess was observed at the time of the earlier observations of the same part of the sky carried out by the same authors, the source Lib γ-1 must be considered variable. The source Tau γ-1 also must be considered variable. In addition to this work,[37] γ radiation from this part of the sky has been recorded in refs. 51 and 58. However, according to preliminary data from SAS-II, which observed the region of 3C 120 for a period of a week, the γ radiation of the object does not exceed a level

10^{-5} photons $(\mathrm{cm}^2\mathrm{sec})^{-1}$, which is an order of magnitude less than the previously recorded flux.

The peculiar galaxy 3C 120 is one of the objects for which Shklovskiĭ[108] predicted bursts of γ rays simultaneously with the increase of the short-wavelength radio radiation. Indeed, the observation of the source Tau γ-1 coincided with one of the largest bursts of radio radiation of the Galaxy.[107,108] The galaxies 3C 120 and PKS 1514-24 belong to a rare class of extragalactic objects—radio galaxies with bright (stellar magnitude 13—15) star-shaped nuclei revealing a rather strong optical variability.[52,109,110] They are similar in their properties to the Seyfert galaxies. The observation of flash γ radiation in two objects of this class even more strongly emphasizes their unusual nature. It is of interest to search for γ-ray fluxes from other sources of this type, which are listed in refs. 109 and 110, from the objects discussed by Shklovskiĭ,[108] and from the Seyfert galaxies. In particular, Gal'per et al.[71] used a spark-chamber γ telescope in the satellite Cosmos 264 to detect excess γ radiation with energy $E_\gamma \geq 100$ MeV from the portion of the sky in which the Seyfert galaxies NGC 4051 and NGC 4151 are located. The flux recorded amounts to 4×10^{-5} photons $(\mathrm{cm}^2\mathrm{sec})^{-1}$ and exceeds the background by four standard deviations.

A variable γ-ray source of ultrahigh energy not identified with any astrophysical object was observed by Stepanian et al.[56] in the constellation Cassiopeia. The variation of intensity of the source was observed for a week.

Thus, the observational data indicate the existence of a number of discrete sources. Although their characteristics, for example, the energy spectrum, have not yet been measured and they have not been reliably identified with astrophysical objects, a general property of the sources has been established—their time variation.[37,124] All of the discrete sources discussed above without exception display in one degree or another a time variability which has the nature of sporadic flashes.

6. SHORT-DURATION FLUXES OF COSMIC γ RAYS

Bursts of cosmic γ-ray fluxes of low energy were observed recently by Klebesadel et al.[111] who carried out constant observations over a period of three years (July 1969 to July 1972) in the satellites Vela 5A, 5B, 6A, and 6B. The Vela satellites had remote circular orbits with a radius of about twenty Earth radii. The detecting equipment on each satellite consisted of six CsI crystals of dimensions 10 cm^3 packaged in a thin case so that electrons with energy $E_e > 0.75$ MeV and protons with energy $E_p > 20$ MeV could be detected. The crystals were located on the surface of the satellite in such a way that the solid angle of the apparatus amounted to 4π. Cases of a sharp increase of the detector counting rate were looked for. During the entire time of observation 16 such events were observed in which the crystal counting rate increased by a factor of ten. Some of the detected events turned out to be recorded in two, three, and even four of the satellites. Histograms of one such simultaneous recording in three satellites are shown in Fig. 9. At the beginning of each histogram is shown the normal counting rate of the apparatus before the burst. The arrows mark individual peaks of the fine structure which are repeated in all three histograms. The time structure of the flashes in the different satellites coincided with an accuracy of 0.8 sec. When the large distances between the satellites is taken into account this simultaneity means that the flashes could be produced by electromagnetic radiation or by fluxes of charged particles of high energy (several GeV) capable of passing through the deflecting magnetic field of the Earth. Such particles would be recorded by the charged-particle detectors existing on the satellites, which, however, did not show changes in counting rate during the detection of the flashes. Consequently, short-duration fluxes of length 0.1 to 30 sec of soft γ radiation with energy 0.2–1.5 MeV were observed. The energy fluxes of the radiation were 10^{-5}–2×10^{-4} erg/cm^2, which is a significant quantity for cosmic rays, comparable, for example, with the radiation of the Sun in the 0.5-MeV line during the entire time of a chromospheric flare ($\sim 10^3$ sec). At the same time there was no correlation of the recorded flashes with solar activity and known flashes of supernovae. The approximate direction of arrival of the γ-ray flux, determined from the delay of the signals in the different satellites, excludes the Sun and the Earth as possible sources of the radiation detected.

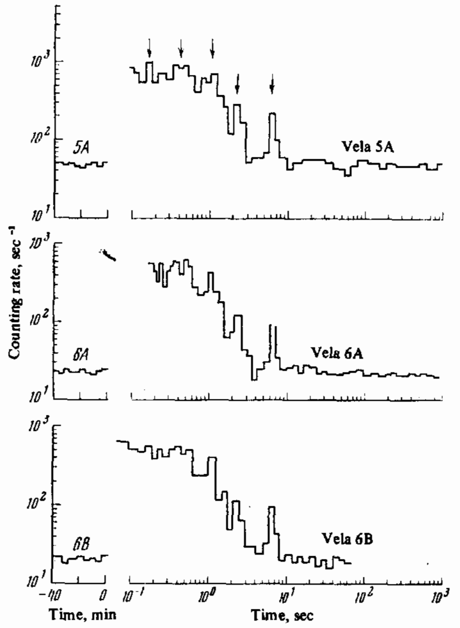


FIG. 9. Example of simultaneous detection of short-duration flux of soft γ rays from the Vela satellites. [111] The arrows show the fine-structure peaks.

The results of this work[111] were confirmed by Cline and Desai[112] by means of observations in the satellites OGO and OMP, which recorded the same flashes. Cline and Desai[112] also note the unusually hard energy spectrum of the radiation, determined from the IMP-6 results, the short time scale (rise time less than 0.05 sec, fall ~1 sec), and the high intensity of the fluxes. Observations are being continued in the satellite IMP-7.

Observation of short-duration flashes of soft γ radiation gives one more convincing proof of the sharp variability of cosmic γ-ray sources. Apparently the investigators have encountered the appearance of a new, previously unknown phenomenon.

7. DEVELOPMENT OF THE TECHNIQUE OF γ-ASTRONOMY OBSERVATIONS

Recent years have been marked by a significant refinement of the technique of the observations, which covers the entire range of γ rays, from detectors of soft radiation to the surface telescopes for ultrahigh-energy γ rays. The methods of identifying cosmic γ rays have been perfected, the geometrical factors and effective areas of the telescopes have been substantially increased, and the energy and angular resolutions have been improved. In addition, considerable attention has been devoted to analysis of the experimental data, in particular, to methods of isolating fluxes from discrete sources.[76-78]

In the soft γ-ray region the method of double Compton scattering is finding steadily increasing application. This method permits reliable identification of γ rays and determination of their direction and energy. Schonfelder and Lichti[86] and White et al.[84] have reported preliminary observations of γ rays with energy 1–10 MeV, carried out by this method with a telescope of scintillation counters. Still better characteristics are expected in a telescope employing liquid detectors, as a result of their higher efficiency and better spatial and energy resolution. Figure 10 shows a diagram of the γ telescope planned by Alvarez et al.[113] for observation of γ rays in the range 0.3–3 MeV. The upper liquid-xenon counter detects the first Compton scattering of a γ ray and measures the coordinates (x_1, y_1) and the energy (E_e) of the recoil electron. The lower multilayer wire chamber filled with liquid xenon determines the location of the second Compton scattering (x_2, y_2) and measures the total energy of the scattered photon (E'_γ). On the basis of the measured values x_1, y_1, x_2, y_2, E_e, and E'_γ and the equations for Compton scattering, the γ-ray energy E_γ and its direction of arrival are calculated. One recorded event determines a circle in the sky on which the γ-ray source is located. The intersection of the circles determined for different events indicates the location of the source. With the existing technology of liquid-xenon detectors (spatial resolution ~10 mm, energy resolution ~10% at 300 keV) it is possible to calculate the source location within a fraction of a square degree. With an effective area of 400 cm^2 the sensitivity of the telescope to the flux from a discrete source is 10^{-3} photons (cm-sec)$^{-1}$ for one observation in a high-altitude balloon.

The method of detecting soft γ-ray flashes used in the Vela satellites[111] has turned out to be extremely efficient. The detectors had a 4π geometry and scanned the entire celestial sphere at once. The measurements were made continuously for a period of three years, which exceeded by several orders of magnitude the duration of any observations carried out up to that time with a directional γ telescope. Measurements were made of the direction of the flux (from the delay of the flashes in the different satellites), the time structure, and the energy spectrum of the flash. This method is obviously also applicable to detection of bursts of high-energy γ rays, and addition of anticoincidence screens would permit reduction of the cosmic-ray background and detection of fluxes of lower intensity, which may be encountered more frequently.

In the energy range 10–50 MeV γ telescopes employing spark chambers have begun to be used successfully.[32,33,49,67,85-87,91] In the telescope of Share et al. (see refs. 33, 49, and 67), which is shown in Fig. 11, a nuclear emulsion is used as a converter. A wide-gap spark chamber permits the region searched for an event in the emulsion to be limited to an area of several square millimeters. Detection of a conversion pair in the emulsion gives better spatial and angular resolution (accuracy of angle measurement ~3° for E_γ = 15 MeV) and also more reliable separation from background events. Great progress has been made in construction of spark-chamber telescopes with automatic readout, intended for use in satellites.[87,114,115] Figure 12 shows a block diagram of the telescope of Fichtel et al.[87,123] with wire spark chambers, which will carry out continuous observations of γ rays with energy $E_\gamma \geq 40$ MeV in the satellite SAS-II (see the note added in proof

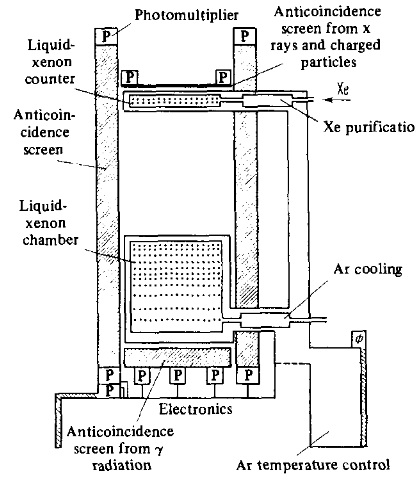


FIG. 10. Liquid-xenon γ telescope intended for detection of 0.3–3 MeV γ rays by double Compton scattering. [113]

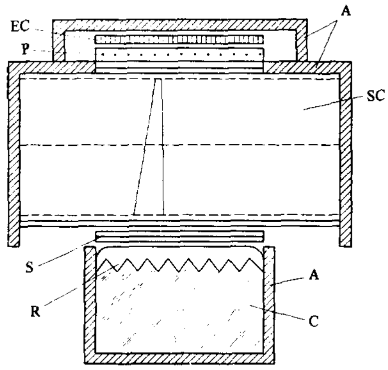


FIG. 11. Block diagram of γ telescope employing spark chamber and emulsion.[33,49] A – anticoincidence counter, p – proportional counter, EC – emulsion converter, SC – wide-gap spark chamber, S – scintillation counter, C – Cerenkov directional counter, R – reflector.

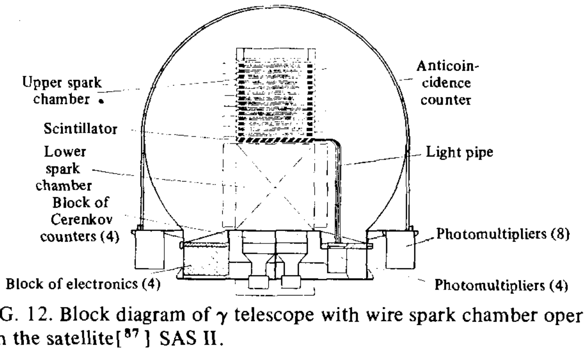


FIG. 12. Block diagram of γ telescope with wire spark chamber operating on the satellite[87] SAS II.

at the end of the present article). The telescope was perfected in the course of several years work with high-altitude balloons[45,78] and has reached the level of reliability which is required for extensive measurements (many months) in a satellite. With a telescope area of 540 cm^2, a geometrical factor of 125 cm^2-sr, an angular resolution of $\sim 2°$ for γ rays of energy 100 MeV, and the long duration of the observations under conditions of comparatively low background (in an almost equatorial orbit) it is expected that the data of SAS-II will permit detection of discrete sources with a flux $\geq 5 \times 10^{-7}$ photons (cm^{2}sec)$^{-1}$.

The technique of γ-ray detection by gas Cerenkov counters at low pressure has advanced. The advantages of this method are the high angular resolution of the detector with comparative simplicity (no track detectors are used—either spark chambers or emulsions), the large effective area, the low background from cosmic-ray particles, and the possibility of measuring γ-ray fluxes with energies of hundreds and thousands of MeV, which not yet possible by other methods. The first measurements with this technique have been made in balloons.[46,90,92] The effective area of the telescopes was 3.4 m^2 (refs. 46 and 90) and 4.5 m^2 (ref. 92). Use of these γ telescopes in satellites is in the future.

Among the planned observations on γ astronomy in the energetic photon region, we should mention the telescopes for the satellites COS-B (1974) and HEAO (1975–1976) (ref. 7). Both telescopes are equipped with wire spark chambers which permit measurement of the γ-ray direction with an accuracy of $\sim 2°$ (for $E\gamma = 100$ MeV) and are intended for detection of γ rays with energy $E\gamma \geq 30$ MeV. The European telescope in COS-B has an area of 576 cm^2 and a geometrical factor 70 cm^2-sr. The American telescope in HEAO-B with a detection area of 4000 cm^2 will have a geometrical factor ~ 2000 cm^2-sr.

In the field of ultrahigh-energy γ rays recorded by surface installations on the basis of the Cerenkov radiation from showers, an important refinement of the method has been suggested by Grindlay.[116,117] He has found a means of separating showers produced by γ rays from showers produced by protons and nuclei. The observation is carried out by several reflectors, some of which are directed to the part of the sky under study, and others shifted in angle in such a way that they detect radiation arising at great depths in the atmosphere. In this case showers from γ rays formed in the upper layers of the atmosphere (in accordance with the conversion and radiation lengths) should be recorded only by the first group of reflectors, while showers produced by nuclear-active particles whose interaction length is greater than the radiation length will give flashes in both groups of reflectors. By connecting the groups in anticoincidence, it is possible to suppress up to $\sim 70\%$ of the counting rate from background proton showers.

8. CONCLUSION

With all the importance of the results of observational γ astronomy obtained in recent years, it appears to us that this is only the beginning. Further progress in this region of astrophysics depends on construction of more up-to-date equipment, and much is being done in this direction. In one of his recent articles L. A. Artsimovich[118] has written that use of the new space technology for extra-atmospheric astronomy should lead to an information explosion which will compel us again to take a new look at many of the most fundamental concepts of the structure of matter. Observational γ astronomy will undoubtedly provide valuable material for this explosion.

Notes added in proof. 1. According to a recent report[125] the γ telescope in SAS-II was shut off for technical reasons in June 1973.

2. In the last few months, experimental studies have been reported (see, for example, ref. 126) which have convincingly confirmed the existence of short-duration flashes of soft γ rays observed in the Vela satellites. It has been established that the maximum intensity of the flashes occurs at an energy of 1000–400 keV. From the improved data of the satellites Vela, IMP, and OSO-7 it has been possible to determine the celestial coordinates of several flashes. The sources are approximately isotropically located in the sky and do not coincide with any astrophysical objects. The isotropy indicates that the sources are either nearby galactic objects at a radius <100 pc,[127] or, on the contrary, remote metagalactic objects at distances > 1 Mpc.[128].

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1) The processes of cosmic γ-ray generation are discussed in more detail in several reviews.[1,3,8].

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