PHYSICS OF OUR DAYS

Intense bursts of cosmic gamma radiation

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The article discusses the history of the discovery of intense bursts of cosmic gamma rays in the Vela group of satellites. A summary is given of the data on observation of gamma-ray bursts in various space instruments. The possibilities of terrestrial observation of phenomena due to the gamma bursts are discussed. Various models of the gamma bursts are analyzed: stellar flares, the activity of neutron stars, nonstationary accretion into compact objects, explosions of supernovae, and the collapse of supermassive bodies in the nuclei of active galaxies. The prospects for futher study of cosmic gamma-ray bursts are discussed.

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1. INTRODUCTION

The rapid development of astrophysics observed in the last decade has two distinctive features. First, contemporary astrophysics involves mainly the study of nonstationary, explosive processes. The tendency toward study of nonstationary processes is perceived in all divisions of astronomy, beginning with study of the physics of the Sun and ending with study of the initial stage of evolution of the Universe. The time, space, and energy scales of nonstationary cosmic phenomena are substantially different (Table I), but all of these processes are connected by a common property—by the important role played in them by high energy particles. The acceleration of nonthermal processes is an inherent property of nonstationary processes in plasma. Under cosmic conditions an appreciable fraction of the total energy of explosive processes goes to fast particles. Fast particles accelerated in nonstationary cosmic processes generate nonthermal radiation over a wide range of wavelengths—from radio waves to gamma rays.

For a detailed study of nonstationary cosmic phenomena, it is necessary to make observations over the widest possible region of the electromagnetic spectrum, including regions inaccessible for terrestrial observations—the infrared, ultraviolet, x-ray, and gamma-ray regions.

This fact has been reflected in another feature of astronomical studies of the last decade—the constantly increasing fraction of extra-atmospheric observation methods. Extra-atmospheric astronomy, particularly x-ray and gamma astronomy, has contributed substantially to the study of nonstationary cosmic phenomena. The discovery of galactic x-ray sources associated with compact stars (neutron stars and black holes) and the study of solar flare x rays are examples of events which decisively influenced the development of current astrophysical ideas.

The development of rocket and space technology not only greatly extended the range of astronomical observations but also led to the appearance of new possibilities for carrying out astronomical research not realized in the traditional fields of terrestrial astronomy.

For example, one of the central problems of contemporary astrophysics has become the study of the final stages of evolution of stars and galactic nuclei. The conclusive stage of evolution of such objects in many cases should occur very violently. The characteristic times of collapse of stars are comparable with the free-fall time of matter and may reach hundredths or thousandths of a second. On the other hand, the expected frequency of such events is low (in our Galaxy it should not greatly exceed one event per year).

TABLE I. Characteristics of nonstationary cosmic phenomena

Cosmic phenomena	Energy release, ergs	Duration, sec
Explosions in nuclei of active galaxies	10^{51}–10^{54}	10^7
Flares of supernovae	10^{48}—10^{50}	10^6
Flares of novae	10^{44}—10^{45}	10^6
Solar flares	10^{30}—10^{32}	10—10^3 (depending on the region)
Bursts of cosmic gamma rays	10^{34}—10^{36} (if the sources are in the Galaxy) 10^{48}—10^{53} (if the sources are beyond the Galaxy)	1—10

As a result, the search for rare events has recently become one of the most popular problems in astronomy (in particular, Weber's report of the possible detection of gravitational waves initiated observations of rare events in the radio and optical regions). Nevertheless, terrestrial observations of rare events have not brought interesting positive results.

Space techniques for astronomical observations have presented to researchers occupied with the search for rare events a new possibility—correlated observations of flaring sources of soft gamma rays by means of space vehicles separated by large distances. Not so long ago it became possible for astronomers to use the system of Vela satellites intended for monitoring nuclear explosions in space. Use of this system has permitted reliable detection of bursts of cosmic gamma rays occurring only a few times per year.

The report of discovery of intense bursts of cosmic gamma rays in satellites of the Vela system [1] evoked wide interest and led to a rapid increase in activity both of theoreticians and of observers. Observation of gamma bursts whose intensity exceeded by several orders of magnitude the intensity of previously observed cosmic gamma sources has initiated a new branch of extra-atmospheric astronomy—the study of flaring sources of hard electromagnetic radiation. Only three years after publication of the first report of gamma bursts, [1] a conference was held at Los Alamos devoted to this phenomenon. [2] At the Los Alamos Conference forty reports were presented on both the observational and theoretical aspects of this problem. Studies of cosmic gamma bursts are being carried on actively also in the Soviet Union at the Institute of Cosmic Research, Academy of Sciences, USSR, at the Nuclear Physics Institute of Moscow State University, and at the Leningrad Physico-technical Institute.[3,4]

The present review discusses questions associated with the observed properties and theoretical interpretation of intense bursts of cosmic gamma radiation. In Sec. 2 we present data on gamma burst observations; in Sec. 3 we discuss theoretical models proposed to explain the nature of the gamma bursts. The last section is devoted to discussion of the long-term prospects for study of gamma bursts.

2. OBSERVATIONS OF INTENSE BURSTS OF COSMIC GAMMA RAYS

a) Discovery of gamma bursts and observations in Vela satellites. Bursts of soft cosmic gamma rays were observed by means of detectors mounted on the satellites of the Vela system (a description of this system can be found in ref. 5). The Vela satellites were placed in circular orbits with a radius of about 120 000 km, in pairs so that the satellites of one pair were on opposite sides of the orbit.

Beginning in 1965 in the satellites of third series (Vela-3A and Vela-3B), short-duration increases in the counting rate of the gamma-ray detectors were recorded.[6] However, the cause of these occurrences remained unexplained at that time—the increases in counting rate could be due to hard radiation from the Sun at the time of flares, to captured radiation, or to instrumental effects.

Data obtained from the satellites of the fourth series, which were put into operation in 1967, permitted the detector readings to be matched in time in several satellites of the system. This narrowed the circle of possible causes of the appearance of gamma bursts. In 1967 in the satellites Vela-4A and Vela-4B a gamma burst was recorded which was not correlated with solar activity, but the data existing at that time did not permit the cosmic nature of the phenomenon to be reliably established.[6]

Significant progress in gamma burst observations was made with the launching of the fifth (1969) and sixth (1970) series of Vela satellites. These space vehicles were equipped with more refined gamma-ray detectors with high time resolution.

In each of the satellites Vela-5A, Vela-6A, and Vela-6B were mounted six scintillation counters with CsI crystals of diameter 19 mm and thickness 25 mm, located in a shield of lead foils 0.25 mm thick. The shield absorbed electrons with energy 0.75 MeV and protons with energy 20 MeV, and also shielded the counter from low-energy photons. The counters detected radiation in the range 0.15—0.75 MeV in the Vela-5 satellite and 0.3—1.5 MeV in the Vela-6 satellite. The detectors placed in the satellites made it possible to obtain complete viewing of the celestial sphere.

The logic scheme of the detectors in the satellites of the fifth and sixth series was intended to identify short-duration pulses of gamma rays. The trigger which turned on the circuit operated in the case when the counting rate in an interval of 0.25 sec exceeded by six standard deviations the background counting rate averaged over the preceding 16 sec. After the circuit was triggered, the detector recorded the counting rate in time intervals increasing in geometric progression (four intervals of 1/64 sec each, four intervals of 1/32 sec each, and so forth up to 128 sec). The time of initiation of the event, measured by the satellite's clock, was also recorded in the memory.

Exact time matching of the reference times has permitted not only separation of cosmic gamma bursts in the background of other events, but also obtaining of information on the celestial coordinates of the sources of gamma bursts from the time difference in recording of the leading edge of the pulses in different satellites of the Vela system (a similar technique was proposed earlier by Giacconi[7]). This method is based on the fact that the time delay in detection $\Delta\tau$ is related with the angle ϑ between the vector l joining the two detectors and the direction to the source by the expression

$$c\Delta\tau = l\cos\vartheta. \qquad (1)$$

Detection of a gamma burst in two separated detectors permits identification in the celestial sphere of a circle in which the source of the gamma burst must be located. When three detectors are used, the possible region of localization is reduced to two points symmetric with respect to the plane of location of the detectors (Fig. 1). Removal of the remaining uncertainty can be accomplished by use of a fourth detector located off the plane passing through the first three instruments. The orbit planes of the Vela system satellites were close together, and therefore the signals from the four detectors did not permit choice of one of the two possible source locations.

From 1969 to 1973, 21 gamma bursts recorded in at least two satellites were observed in the Vela satellites. A preliminary catalog of gamma bursts in which data are given on the time of the bursts, their location in the celestial sphere, and the total energy recorded during the burst has been published by Klebesadel et al.[8] (Table II).

The photonic nature of the observed gamma bursts is quite reliably established at the present time. Charged-particle and neutron detectors located in the Vela satellites showed no increase in counting rate at the time of the gamma bursts.[1] In addition, gamma bursts were recorded in the same satellite located both outside and inside the Earth's magnetosphere, and no action of the Earth's magnetic field on the propagation of the bursts was noted.

On the basis of data on the location of gamma-burst sources in the celestial sphere, Klebesadel et al.[1] concluded that the gamma bursts are not associated with the Sun, Earth, Moon, or other planets.

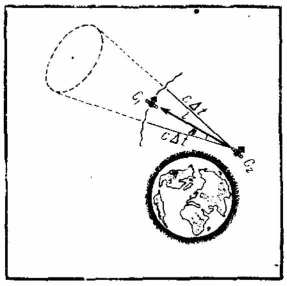

FIG. 1. Determination of the direction to a source of gamma bursts. The leading edge of the gamma burst is recorded first by satellite C_1, and sometime $\Delta\tau$ later by satellite C_2. Knowing the distance l between the satellites, we can determine the angle ν between the direction to the source of the gamma burst and the straight line joining the satellites. The angle ν gives the circle in the celestial sphere in which the burst source is located.

TABLE 11. Catalog of gamma bursts observed in the Vela satellites

Number of bursts	Time T (date and seconds)	Coordinates of bursts					Flux, ergs/cm²
		For three satellites		For two satellites			
				Center of circle		Radius, deg	
		Equatorial	Galactic	Equatorial	Galactic		
67—1	2.7.67 51568						$2\cdot10^{-5}$
69—1	3.7.69 26233			191+20	294+83	29	$2\cdot10^{-4}$
69—2	7.10.69 26791			236+33	52+52	19	$2\cdot10^{-5}$
69—3	17.10.69 11927			27—27	215—77	86	$4\cdot10^{-5}$
69—4	17.10.69 78113			156+01	244+46	83	
70—1	14.6.70 18416		Solar				
70—5	10.7.70 19066						
70—2	22.8.70 60751	144+61 209—29	153+44 320+31				$1\cdot10^{-4}$
70—3	1.12.70 72059			91—29	235—22	76	$4\cdot10^{-5}$
70—4	30.12.70 25337	120+10 149—30	212+20 264+19				$3\cdot10^{-4}$
71—4	2.1.71 69056	216+60 225+03	103+54 1+50				$1\cdot10^{-4}$
71—6	27.2.71 62855						
71—2	15.3.71 40827			4—21	72—80	82	$1\cdot10^{-5}$
71—3	18.3.71 55685	69+12 115—71	185—22 283—22				$1\cdot10^{-4}$
71—4	21.4.71 11919			247+34	55+43	83	$3\cdot10^{-6}$
71—5	30.6.71 63059			27—30	228—77	52	$5\cdot10^{-5}$
72—1	17.1.72 63556	104+09 136—29	206+06 255+12				$7\cdot10^{-4}$
72—2	12.3.72 57195	277+01 298+35	31+05 71+04				$5\cdot10^{-4}$
72—3	28.3.72 49588			283+22	53+09	86	$1\cdot10^{-4}$
72—6	27.4.72 39512						
72—4	14.5.72 13591	176+78	127+39				$2\cdot10^{-4}$
72—5	1.11.72 68206	11+19 309—56	121—44 342--37				$7\cdot10^{-6}$
73—1	7.5.73 29072	342+56 254—33	107—03 351+06				$6\cdot10^{-5}$
73—2	10.6.73 75582			25—36	255—76	61	$1\cdot10^{-4}$

The distribution of the gamma bursts over the celestial sphere (in galactic coordinates) is shown[9] in Fig. 2. No clearly expressed anisotropy due to the disk structure of the Galaxy is observed. Therefore the sources of gamma bursts must be located either in the immediate vicinity of the Sun at distances less than the thickness of the galactic disk or beyond the limits of our Galaxy. The observational data obtained up to this time have been insufficient for a choice between these two possibilities.

Nevertheless there are several arguments which support the galactic nature of the gamma burst sources. In the first place, the gamma bursts are nonuniformly distributed in galactic longitude[10-12] (Fig. 3, ref. 10). This fact may be due to the spiral structure of the Galaxy, since the Sun is located on the inner side of the spiral arm.

In the second place, the weak gamma bursts are distributed anisotropically and are grouped near the galactic plane.[13,14] The statistical reliability of these arguments is poor and the question of localization of the sources of gamma bursts still remains open.

Study of the distribution of gamma bursts in flux (Fig. 4, ref. 12) could become a powerful means of investigating the nature of their sources (as occurred, for example, with extragalactic radio sources). However, for this purpose it is necessary to have increased observational statistics.

The duration of the gamma bursts varies from tenths of a second to tens of seconds. The intensity variation of the radiation during a burst is quite varied—single pulses have been observed, and sequences of pulses of duration several seconds separated by intervals of tens of seconds (Fig. 5, refs. 6 and 8). The intensity of the radiation during the gamma bursts changes very rapidly; variations have been observed with a duration of 1/64 sec, the minimum resolvable in the detectors of the Vela satellites.[15]

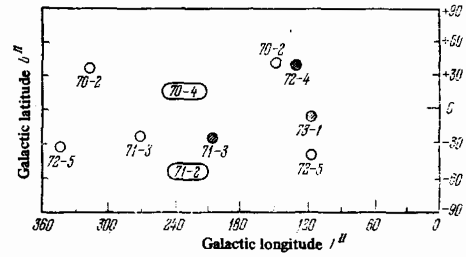

FIG. 2. Galactic coordinates of gamma bursts observed by at least three Vela satellites.

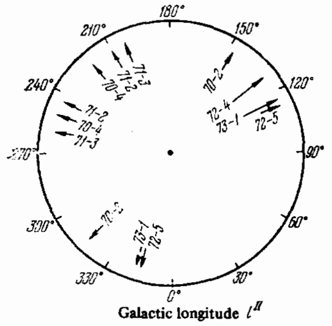

FIG. 3

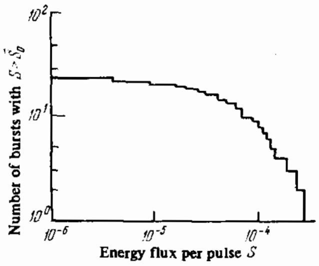

FIG. 4

FIG. 3. Distribution of gamma bursts in galactic longitude.
FIG. 4. Distribution of gamma bursts in observed flux.

b) **Observations of the gamma bursts discovered in the Vela satellites in other space vehicles.** The instruments in the Vela satellites did not permit investigation of the spectral characteristics of the gamma bursts. The energy spectra of the gamma bursts were first obtained in the gamma-ray monitor[16,18] placed on the satellite IMP-6. This satellite was placed in a highly elongated orbit with an apogee of 200 000 km in 1971. By means of gamma-ray detectors placed on this satellite, spectra were obtained of six of the eight gamma bursts recorded in the Vela satellites during this period. The gamma-ray detector consisted of a scintillation counter with a CsI crystal of diameter 57 mm and length 38 mm, surrounded by an anticoincidence plastic scintillator. The apparatus recorded photons with energy from 50 to 1100 keV; the time resolution was 2—3 sec.

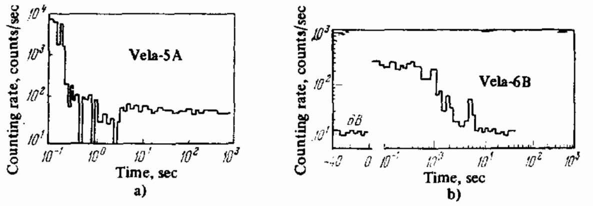

FIG. 5. Time change of gamma flux intensity of bursts observed on October 17, 1969 (a) and January 2, 1971 (b).

The gamma burst spectra measured in the IMP-6 apparatus were approximated by an exponential function

$$\frac{dn}{dE}=I_0\exp\left(-\frac{E}{E_0}\right). \tag{2}$$

Numerical values of I_0 and E_0 expressed in photons/cm^2-keV and in keV, respectively, are listed in Table III.

The characteristic energies E_0 of the gamma bursts are grouped around 150 keV. The flashes observed on IMP-6 consisted of short pulses with a hard spectrum (E_0 = 150 keV) superimposed on a slowly varying soft component (E_0 = 75 keV). No line sources of gamma rays were observed in the bursts. The observations in IMP-6 did not show sharp variations in the energy spectrum during individual pulses.

One of the gamma bursts recorded on May 14, 1972, was observed also in the hard x-ray region[19,20] in the instruments of the satellite OSO-7. The OSO-7 satellite was in a circular orbit at a height of 550 km located inside the magnetosphere. Its detectors (scintillation spectrometers with NaI crystals) recorded radiation in the ranges 7–500 keV and 11–300 keV. The time resolution of the instruments was not very high—10–15 sec.

The observations on the OSO-7 satellite instruments showed that the spectrum of bursts in the hard x-ray region differs from the spectrum in the gamma-ray region (Fig. 6):

$$\frac{dn}{dE}\backsim E^{-\alpha}, \tag{3}$$

where α varies over the range 0.6–1.4. The exponent of the spectrum increased with decrease of the intensity, which indicated a slower falloff in the power of radiation at low energies.

It is interesting to note that the region of the celestial sphere in the direction of a given gamma burst was scanned by the instruments for a period of twelve hours before and after the burst. No radiation was observed. The upper limit at the 3σ level (2×10^{-3} photons/cm^2-sec in the range 10.6–14.4 keV) is 400 times less than the maximum intensity during the burst.

Interesting results were obtained in the gamma detector mounted in the satellite 1972–076B. This satellite, which moved in a polar orbit of height 750 km, contained a germanium semiconductor spectrometer with high energy and time resolution.[21-23] The apparatus detected photons with energy 50–2500 keV with an energy resolution of 3.5 keV. Each of the channels of the 4096-channel analyzer was interrogated once in each millisecond.

TABLE III. Characteristics of the spectrum of gamma bursts

Number of bursts	Part of burst studied	I_0, photons/cm^2-keV	E_0, keV
71–2	Peak of second subpulse	1.9	156
71–3	Fall of first subpulse	1.8	74
71–5	Peak of first subpulse	0.7	276
71–5	Peak of second subpulse	5.5	142
71–5	Fall of second subpulse	0.7	110
72–1	Fall of first subpulse	0.1	138
72–1	Peak of second subpulse	0.35	184
72–1	Fall of burst	0.11	170
72–3	Peak of second subpulse	0.50	238
72–4	Peak of first subpulse	0.8	166
72–4	Peak of second subpulse	0.8	152

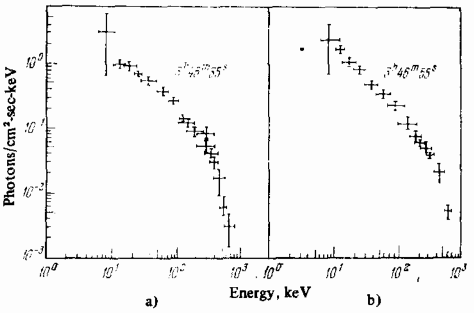

FIG. 6. Energy spectra of first (a) and (b) sub-pulses of the gamma burst recorded on May 14, 1972. The spectral observations were made in the satellites OSO-7 and IMP-6.

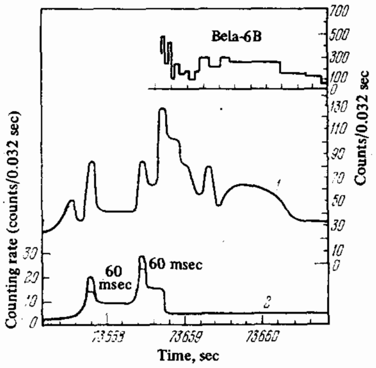

FIG. 7. Time dependence of counting rate of apparatus during the burst of December 18, 1972 (the observations were made in the satellite 1972-076B). 1–Germanium spectrometer, 2–anticoincidence plastic counter. For a comparison we have shown in the figure the time structure of the pulse according to the data of the Vela satellite.

Figure 7 shows the counting rate of the apparatus as a function of time during the burst of December 18, 1972. The gamma burst has a complex structure; at least six separate sub-bursts are observed in it. The increase in the counting rate in the instruments of the 1972–076B satellite began 1.2 sec before the logic circuit of the detectors in the satellite Vela-6B was turned on. In this burst no very short sub-bursts with duration from 5 μsec to 32 msec were observed. The spectra obtained in the germanium spectrometer can be fitted either by an exponential or a power law within the statistical errors (Fig. 8).

The gamma bursts observed by the Vela system were noted also in other instruments on board the various satellites Cosmos-461,[3] Uhuru,[24] TD-1A,[25], OSO-6,[26] and OSO-5.[27,28]

In some cases the detection of the gamma bursts in these instruments permitted more accurate location of the sources in the celestial sphere.[8] Data on the gamma burst observations are given in Table IV.

c) **Search for new x-ray and gamma bursts.** The discovery of gamma bursts in the Vela satellites initiated a search for similar phenomena by means of x-ray and gamma-ray detectors mounted in various space vehicles. In spite of the fact that none of these instruments had such high selectivity to gamma-ray pulses as the detectors of the Vela satellites, their higher sensitivity or broader energy range permitted observation of rather

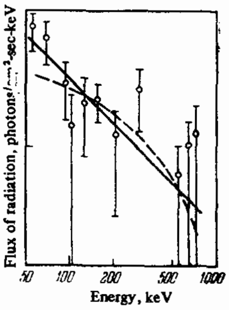

FIG. 8. Energy spectrum of the gamma burst of December 18, 1972, measured in the satellite 1972–076B.

TABLE IV. Summary of observations of gamma bursts

Number of bursts	Space vehicles									
	Vela	OSO-7	IMP-6	Uhuru	SAS-2	OSO-6	OGO-5	TD-1 A	Apollo-16	Cosmos-461
67—1	+	—	—	—	—	—	—	—	—	—
69—1	+	—	—	—	—	—	—	—	—	—
69—2	+	—	—	—	—	—	+	—	—	—
69—3	+	—	—	—	—	—	—	—	—	—
69—4	+	—	—	—	—	—	—	—	—	—
70—1	+	—	—	—	—	—	+	—	—	—
70—2	+	—	—	—	—	—	+	—	—	—
70—3	+	—	—	—	—	+	+	—	—	—
70—4	+	—	—	—	—	—	—	—	—	—
70—5	+	—	—	—	—	—	—	—	—	—
71—1	+	—	—	+	—	—	—	—	—	—
71—2	+	—	+	—	—	—	+	—	—	—
71—3	+	—	+	+	—	—	+	—	—	—
71—4	+	—	—	+	—	—	—	—	—	—
71—5	+	—	+	+	—	—	+	—	—	—
72—1	+	—	+	+	—	—	—	—	—	+
72—2	+	—	—	—	—	—	—	—	—	—
72—3	+	—	+	—	—	—	—	—	—	—
72—4	+	+	+	—	—	—	—	—	—	—
72—5	+	—	—	—	—	—	—	+	—	—
72—6	+	—	—	—	+	—	—	—	+	—
73—1	+	—	—	—	—	—	—	—	—	—
73—2	+	—	—	—	+	—	—	—	—	—

interesting phenomena, although the degree of reliability of the results obtained is lower than in the measurements in the Vela satellites.

The space ships Apollo-15 and Apollo-16 contained x-ray spectrometers intended for study of the chemical composition of the Moon's surface from a lunar orbit.[29,30] These spectrometers operated in the soft x-ray region from 1 to 3 keV. Apollo-15 and Apollo-16 also contained spectrometers for gamma rays with energies above 200 keV.

In the course of twenty hours of observations during the flight from the Earth to the Moon and back, two x-ray bursts of duration about two minutes and two more of somewhat longer duration were observed. Figure 9 shows a recording of the x-ray burst observations on June 25, 1971. The rise time of the pulse is somewhat less than a minute, and the maximum intensity is several times that of the brightest x-ray source, Scorpio X-1.[31] No hard gamma rays with energy above 200 keV were observed during this burst.

It was not possible to establish the direction to the source of the x-ray burst, since the width of the directional pattern of the apparatus was large (about 50°). However, the frequency of appearance of the bursts turned out to be much greater than for the gamma bursts observed in the Vela satellites—10^4 bursts per year over the entire celestial sphere, as against 5–7.

Nevertheless, Gorenstein et al.[31] were not completely convinced that the observed bursts were x rays. Similar effects could be produced by a burst of electrons with a sufficiently soft energy spectrum, accelerated in plasma layers in the region near the Moon. There were no low energy electron detectors on the Apollo ships,

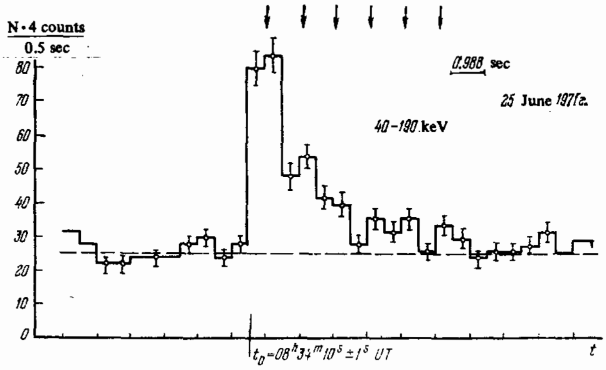

FIG. 9. Total counting rate during the flare of June 25, 1971, recorded in the satellite Cosmos-428 in the range [4] 40–190 keV. The arrows indicate possible locations of maxima with a period of 1 sec.

and therefore the explanation cannot be rejected. However, the ratio of the counting rates of the instruments comprising the spectrometer was more characteristic of x rays than electrons.

A high frequency of increases in the counting rate was observed also in the hard x-ray detector of the OSO-7 satellite.[32] In 261 days of observations, 374 bursts were observed, which, when the solid angle of the apparatus is taken into account, corresponds to a burst frequency of 10^4 per year in the entire celestial sphere. Hard x-ray bursts were observed also in the satellite Cosmos-428.[4] The time structure of the bursts is similar to the structure of the gamma bursts (see Fig. 9), but their spectrum is softer. Babushkina et al.[4] note that the location of the bursts in the celestial sphere coincides with the location of the strong discrete variable sources of hard x-rays observed in the same apparatus.[4,33,34]

Figure 10 shows the distribution of the x-ray bursts observed in the satellite Cosmos-428. The very high frequency of this phenomenon should be noted—the total intensity of bursts comprises an appreciable part of the diffuse x-ray background. The set of observations of x-ray bursts does not exclude the possibility that this phenomenon is encountered much more frequently than the gamma bursts observed in the Vela satellites. Nevertheless, conclusive proof of x-ray bursts can be obtained only after correlated observations have been carried out in several space vehicles.

The instruments on the satellite IMP-6 had an order of magnitude greater sensitivity than those on the Vela satellites. Observations in these instruments have shown that the frequency of bursts with a small flux in the soft x-ray region is low and is consistent with the $S^{-3/2}$ law characteristic of an isotropic distribution of sources (where S is the radiation flux during a burst). Observations of gamma bursts in balloons[35,36] also have not led to observation of a large number of events (however, as the result of the short exposure of the apparatus, the upper limit obtained for the frequency of events is rather high: $N \leq 2 \times 10^4$ bursts per year in the entire celestial sphere for a sensitivity 10^{-7} erg/cm^2 in the region 100–400 keV).

d) **Terrestrial observations of phenomena associated with gamma bursts.** Pulsed x-ray and gamma radiation can be observed by its action on the upper layers of the atmosphere. The ionization produced by hard x-rays in the lower ionosphere should lead to a shift in the phase

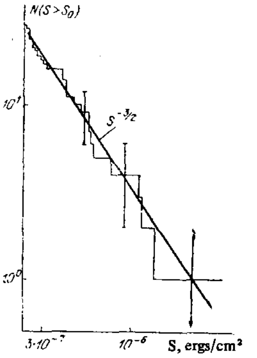

FIG. 10. Distribution of x-ray bursts observed in the satellite Cosmos-428, as a function of flux.

of long-wave radio signals and to an additional absorption of radio waves. Calculations show that the ionospheric effects produced by gamma bursts are at the threshold of sensitivity of contemporary apparatus.[37-39] The action of hard x rays on the upper atmosphere can appear also in optical fluorescence, and this effect has been used to search for bursts of hard gamma rays with energies of hundreds of MeV.[40,41]

Nevertheless, the sensitivity of terrestrial methods of detecting x-ray and gamma bursts is significantly lower than for detectors located in space vehicles.

Very great interest is presented by the terrestrial search for phenomena in the radio and optical regions associated with gamma bursts. The discovery of radio and optical accompaniments of gamma bursts would play an important role both in clarifying the nature of their sources and in solution of other astrophysical problems. Optical radiation accompanying gamma bursts can arise in various types of sources—in stellar flares, in bombardment of the normal component of a close binary system by hard radiation, and so forth, and study of its properties would provide important information on the nature of the sources of gamma bursts. Study of the radio radiation associated with gamma bursts of metagalactic origin could provide valuable information on the properties of the intergalactic gas.[42]

Observations of infrequent bursts of radio and optical radiation are exceptionally complicated as the result of the presence of a large number of background events both of natural and of artificial origin. Up to the present time no optical or radio bursts associated with gamma bursts have been observed. Nevertheless, there is a large margin of sensitivity of the instruments for detection of such phenomena and we can hope that in the coming years important results will be obtained in this area.

Observations of the optical accompaniment of the bursts have been carried out in the Prairie Network system, which was intended for observation of the location of meteorite falls.[43] In each of the 16 stations of the system, four cameras have been installed with objectives 5 m in diameter and a viewing angle of 90°. This system could observe optical flashes with a brightness to the sixth stellar magnitude.

Favorable observation conditions—clear weather, accurate knowledge of gamma-burst coordinates—occurred only for two bursts. No optical flashes were noted at the time of the bursts, and the upper limit for the intensity of optical radiation of a burst was $m_\nu \geq +6$ or $F_\nu \leq 1.2 \times 10^{-22}$ erg/cm²-sec-Hz.

The search for radio bursts in the meter, decimeter, and centimeter regions is being carried out by means of receivers separated by large distances, with antennas having a broad directional pattern.[44-50] No positive results have been obtained. The upper limits of the flux of radio radiation accompanying gamma bursts are 10^{-21}–10^{-22} W/m²-Hz. The results of the searches for radio bursts are reported in the review by Troitskiĭ et al.[51]

3. THEORETICAL INTERPRETATION OF GAMMA BURSTS

a) General requirements on models of gamma bursts. All models proposed for interpretation of gamma bursts attempt to explain the short duration of the observed phenomenon and the exceptionally high degree of energy concentration. In order to explain the unusual properties of gamma bursts, some hypotheses draw on extravagant processes which have not been used previously. Nevertheless, the greater part of the hypotheses advanced utilize for interpretation of gamma bursts processes which have been well recommended in high energy astrophysics.

From the approximate isotropy of the gamma burst distribution over the celestial sphere, it follows that their sources must be either at small distances less than the thickness of the galactic disk ($r \lesssim 100$ pc), or at large, metagalactic distances ($r \gtrsim 10$ Mpc). The existing observations do not yet permit a choice between the possible localizations of the gamma burst sources (however, there are some indications in favor of the galactic nature of gamma bursts,[10-12] although their statistical reliability is poor).

Models of galactic sources of gamma bursts are discussed in part b) of this section. The energy release of galactic gamma bursts ($Q \lesssim 10^{38}$ ergs) is small in comparison with the energy release of metagalactic bursts. This has permitted many authors to use for explanation of gamma bursts the mechanisms well known in high energy astrophysics: dissipation of the energy of the magnetic field in current layers, accretion into compact objects, and so forth. The main feature of galactic gamma burst sources is their large number in comparison with galactic sources of x-rays and gamma rays. While the number of x-ray sources in the Galaxy is of the order 10^2, the number of galactic sources of gamma bursts must exceed 10^5, since in the closest region of the galactic disk with radius of the order of hundreds of parsecs there should be about ten sources.

In part c) we discuss models of metagalactic gamma burst sources. The energy requirements for metagalactic sources are quite severe: the energy released in a time interval of the order of seconds must, depending on the distance from the source, amount to 10^{48}–10^{53} ergs. All models proposed up to this time for gamma bursts of metagalactic origin are associated with the collapse of stars or starlike massive objects in the nuclei of active galaxies.

In spite of the fact that at the present time a final choice between models of gamma-burst sources cannot be made, a review of the existing hypotheses is of definite interest. The great diversity of the models advanced for explanation of the nature of gamma bursts reflects the wealth of phenomena which can be observed with increase of the sensitivity of existing x-ray and gamma telescopes.

Even in the case that the proposed models have no relation to the gamma bursts observed at the present time, the phenomena predicted by the models which have been advanced will exist, and their investigation should lead to a deeper understanding of processes in nonstationary cosmic objects.

In conclusion of this section we will briefly summarize the main results of gamma-burst observations, which must be explained in any model proposed for their interpretation.

1) The total energy flux in a pulse amounts on the average to 10^{-4} erg/cm^2; the range of observed fluxes is from 5×10^{-4} to 3×10^{-6} erg/cm^2.

2) The observed frequency of bursts is about five events per year in the entire celestial sphere.

3) No clearly expressed anisotropy of the angular distribution of gamma bursts is observed.

4) The duration of the bursts amounts to several seconds on the average, varying over the range from 0.1 to 80 sec. The characteristic time of the intensity fluctuations during a burst can be as small as hundredths of a second.

5) The spectra of gamma bursts can be approximated by an exponential function $F(E)\propto\exp(-E-E_0)$; $E_0\sim150$ keV.

Let us turn now to discussion of specific models of sources of gamma bursts.

b) **Galactic sources.** 1) Flaring stars. One of the first hypotheses as to the nature of gamma bursts was that of Stecker and Frost[52] according to which the observed gamma radiation is produced in stellar flares, similar to solar flares. An argument in favor of this hypothesis has been the similarity between the durations and spectra of the gamma radiation of the bursts and the hard x rays of solar flares.[52,53]

It is known that the source of energy of solar flares is the energy of the magnetic field: At the time of flares, the magnetic energy is transformed into energy of plasma particles as the result of dissipation of the magnetic field near its zero points.[54]

Hard x-ray and gamma radiation can arise in the following processes:

a) bremsstrahlung of nonthermal electrons accelerated in the flare process;

b) bremsstrahlung of thermal electrons by hot thermalized plasma;

c) inverse Compton scattering of stellar radiation by accelerated ultrarelativistic electrons;

d) synchrotron radiation of ultrarelativistic electrons in strong magnetic fields.

In solar flares the hard x rays are due to the first mechanism. However, this mechanism is rather inefficient—the fraction of the electron energy transformed into nonthermal bremsstrahlung on complete stopping of the electrons[55] is about 10^{-5}.

In order to explain the observed radiation fluxes of gamma bursts by a flare in a star located at a distance of 10—100 pc, it is necessary to assume that the energy radiated in the gamma-ray region is 10^{36}—10^{38} ergs. If the fraction of the energy transformed to gamma rays in the flare is the same as in solar flares (according to ref. 53), then the total energy of the flare will amount to 10^{41}—10^{43} ergs. This energy would have to be emitted in other regions—optical, ultraviolet, or x-ray, which has not been observed up to the present time.

The efficiency of a gamma flare can be increased if we assume that the gamma rays arise in bremsstrahlung of hot plasma with a temperature of the order of 10^9 °K. However, the existence of rapid fluctuations in the intensity of the gamma bursts imposes severe limitations on the possible parameters of the sources. The characteristic time of the fluctuations of the flux of gamma radiation cannot be shorter than the time of cooling of the radiating plasma, which is

$$t=2\cdot10^{11}\sqrt{T}n^{-1}\ \text{sec} \qquad (4)$$

At a temperature $T = 1.5\times10^9$ °K corresponding to a spectrum (2) with $E_0 = 150$ keV and a fluctuation time $\sim1.6\times10^{-2}$ sec, the concentration of the plasma in the radiating region must exceed 6×10^{17} cm^{-3}.

This high concentration in normal stars is achieved in layers lying significantly below the photosphere, and only in the case of compact stars, in particular, white dwarfs, will this concentration correspond to the optically thin surface layer of the star.

White dwarfs—as sources of gamma bursts—have a further advantage: the magnetic fields observed at their surfaces reach in some cases[56] 10^7 Oe. Such strong magnetic fields can serve as a source of energy for intense stellar flares.

Let us turn now to discussion of gamma-burst models in which hard electromagnetic radiation is generated by ultrarelativistic electrons.

Brecher and Morrison[57] have proposed a gamma-burst model in which gamma radiation is produced by scattering of the thermal radiation of a star, with photon energies of ~1 eV, by electrons with energies of 50—500 MeV ejected from the star during a flare and propagating along the lines of its magnetic field. In this case the gamma radiation can be concentrated in a very small solid angle, which produces the total gamma-flare power necessary for explanation of the observed bursts. However, the gain in power is achieved in this case at the expense of an increase in the number of sources necessary to explain the observed frequency of appearance of gamma bursts. It should be noted that in this model the efficiency of transformation of the energy of the relativistic electrons into gamma radiation is low,[57] $\sim10^{-5}$.

In strong magnetic fields of compact objects, another mechanism of gamma burst generation is possible—synchrotron radiation of ultrarelativistic electrons. In the magnetic fields of the order 10^7 Oe observed in white dwarfs, synchrotron radiation falls in the gamma-ray region for an electron energy of the order of 10^9 eV.

Observational verification of the hypothesis of stellar flares can be obtained by identification of gamma-burst sources with specific cosmic objects and subsequent performance of correlated observations in different regions.

2) Nonstationary accretion into compact objects. The luminosity of galactic sources of gamma bursts is comparable with the luminosity of stationary x-ray sources associated with compact objects in close binary systems.

The source of energy of these x-ray sources is the incidence of matter leaving a normal star into a compact object—so-called accretion.

A distinctive feature of galactic x-ray sources in close binary systems is the strong variability. The characteristics times of the variability vary from days or hours to milliseconds.[58-60]

This feature of accretion into compact objects and the possibility of assuring a high luminosity and a hard radiation spectrum has led to appearance of hypotheses that gamma bursts are associated with accretion into compact objects.[61-63]

Nevertheless, such sources of gamma bursts should differ from stationary x-ray sources in at least two aspects:

a) As noted above, the number of sources of gamma bursts in the Galaxy should exceed by more than three orders of magnitude the number of stationary x-ray sources.

b) The luminosity of gamma-burst sources at the time of the flare exceeds the luminosity in the quiet state by more than five orders of magnitude.

At the present time, two models have been proposed within the framework of this hypothesis, which solve in different ways the question of the nature of the accumulating material.

The first model, proposed by Harwit and Salpeter[61] and independently by Shklovskiĭ[62] associates gamma bursts with the accretion of comets into single white dwarfs or neutron stars. The mass of the comets, which according to crude estimates[63] is $10^{16}-10^{21}$ g, corresponds in order of magnitude to the mass of accumulating gas necessary to explain the energetics of gamma bursts.

However, to explain the observed frequency of gamma bursts even with the most favorable assumptions regarding the concentration of neutron stars in the Galaxy ($n \sim 0.03$ pc^{-3}),[64] it is necessary to assume that the density of the comet swarm around a star is at least two to three orders of magnitude higher than around the Sun. This assumption, like the possibility of survival of a comet swarm in formation of a neutron star, appears unlikely.

The second model explains the production of gamma bursts by accretion of gas ejected in the flare of a normal star into a compact object which forms with the normal star a close binary system.[65]

To explain gamma bursts in terms of this model it is necessary to assume that the mass of gas ejected in stellar flares is significantly greater than the mass of gas ejected in solar flares, particularly if accretion into white dwarfs occurs.

There is no doubt as to the existence of such sources. However, their identification with observed gamma bursts encounters definite difficulties. The principle of these is the need of explaining the short duration of the observed gamma bursts, hundreds of times shorter than the time of flight of the gaseous cloud from a flaring star to a compact object.

3) Activity of neutron stars. The following model of gamma bursts[66] also associates this phenomenon with the activity of neutron stars. However, in contrast to the preceding models, it assumes that the gamma burst is generated as the result of ejection from young neutron stars of material consisting of a mixture of superheavy nuclei and free neutrons. Gamma radiation is produced on fission of the superheavy nuclei, β decay of radioactive elements, and radiative capture of the free neutrons.

The energy source providing this ejection could be the nuclear energy stored in the shell of the neutron star, due to a nonequilibrium chemical composition,[67] or the energy released in melting of the solid nucleus of a neutron star.[68]

If we assume that the increase of the kinetic energy in the filaments in the Crab nebula observed some time after an abrupt change in period of the pulsar NP 0532 is due to ejection of matter from a neutron star, we can show that the mass of ejected material is $\sim 10^{21}$ g. Ejection of this quantity of nonequilibrium matter from a neutron star should lead to an energy release of $\sim 10^{38}$ ergs, which is more than sufficient to explain the energetics of gamma bursts.

The spectrum of primary gamma rays observed in nuclear interactions is very complex, and its maximum should occur at an energy of the order of 1 MeV. To explain the observed spectrum it is necessary to assume that the photons decrease their energy by an order of magnitude in the process of leaving the cloud of expanding material.

Gamma bursts simultaneous with jumps in the period of pulsars have not yet been observed. It is possible that this is due to the considerable remoteness of the most active pulsars. Estimates show that to detect gamma bursts from the pulsars NP 0532 and PSR 0833 it is necessary to increase the detector sensitivity by about an order of magnitude.

Another possibility for production of gamma bursts in processes associated with the activity of neutron stars lies in perturbations of the magnetosphere of pulsars, due either to readjustment of the inner layers of a neutron star[69] or to instability of the magnetosphere itself.[70]

c) Metagalactic sources. 1) Explosion of supernovae. Several years before the discovery of gamma bursts, Colgate[71] predicted the existence of an intense pulse of gamma radiation arising in explosion of a supernova. According to Colgate's hypothesis, the gamma radiation is produced on arrival of a relativistic shock wave at the surface of the presupernova.

Formation of the shock wave in the presupernova is due to the intense energy release near its center, for example in collapse of the nucleus of the star. The shock wave, propagating in a medium with decreasing density, as it approaches the surface of the star will increase its velocity and, when the fraction of the mass in front of the shock wave reaches 10^{-4} of the mass of the star (for a stellar mass $5M_\odot$ and a minimum radius of 2×10^9 cm), the wave becomes relativistic. The temperature of the heated gas is determined by the expression[71]

$$aT^4 = 2\gamma_s^2 \rho_0 c^2, \qquad (5)$$

where ρ_0 is the density of the gas in front of the shock wave, $\gamma_S = 1/\sqrt{1-(v/c)^2}$, v is the velocity of the gas behind the shock wave front, and a is a constant equal to 7.56×10^{-15} erg/deg^4.

Near the surface of the star the temperature of the heated gas reaches 2×10^9 °K. When the optical thickness of the gas in front of the shock wave front becomes of the order of unity the heated gas generates a pulse of gamma rays.

The average energy of the photons in the system associated with the gas behind the shockwave front is 3 kT. As a result of the Doppler shift due to the relative motion of the heated gas ($\gamma_S \approx 1.5 \times 10^3$), the average energy of the observed photons increases, reaching

$$h\nu = 3kT \sqrt{\frac{1-(v/c)}{1+(v/c)}} \approx 6kT\gamma_s \approx 2\ \mathrm{GeV}. \tag{6}$$

The duration of the burst of gamma rays is[71]

$$\tau \approx \frac{R}{2\gamma_s^2 c} \approx 1.5 \cdot 10^{-5}\ \mathrm{sec}. \tag{7}$$

The total energy radiated in the gamma region in explosion of a supernova with $M = 5M_\odot$ and $R = 2 \times 10^9$ cm reaches 5×10^{47} ergs. This energy release would be sufficient to explain the observed flux of gamma bursts if the supernovae generating these bursts are located in the closest galaxies. However, the other parameters of the gamma radiation of supernovae—the average photon energy and the duration of the burst—differ considerably from the observed characteristics of gamma bursts. The bursts of hard gamma rays predicted by Colgate have not been observed up to this time.

The increase in the radius of a supernova up to 10^{12} cm proposed in a recent article by Colgate[72] provides the possibility of bringing the duration and energy of gamma bursts to the observed values. However, in this case the problem arises of providing the necessary energy yield, since a relativistic shock wave in stars with large radii and small parabolic velocities is very weak, and the energy radiated in the gamma region is insufficient to explain the observed gamma-radiation fluxes.

Another difficulty of this model is due to the fact that on arrival of the shock wave at the surface of the presupernova, a single burst of gamma radiation should be observed with a monotonic decrease and increase of the flux, while the observed gamma bursts have, as a rule, a complex structure (see Fig. 5).

2) Collapse of stars. Another process which could provide the energy of metagalactic gamma bursts is gravitational collapse. We will discuss models based on the assumption of gravitational collapse of stars as the cause of gamma bursts.

Even before the discovery of gamma bursts, LeBlanc and Wilson[73], in discussing the collapse of a rotating magnetic star with a mass $7M_\odot$, showed that in the process of collapse, matter with a mass of $\sim 2 \times 10^{31}$ g is ejected from the star along its axis of rotation, in which the temperature, density, and magnetic field strength are respectively 3.5×10^9 °K, 10^6 g/cm^3, and 10^{13} Oe. The thermal radiation of this ejection, according to Jelley,[74] may be responsible for production of gamma bursts. If the distance to the collapsing star does not exceed hundreds of megaparsecs, the internal energy of the ejected gas ($\sim 10^{49}$ ergs) is sufficient to explain the observed flux of gamma rays. This model can explain the observed frequency of gamma bursts. However, the prediction of the spectral properties of gamma bursts on collapse of magnetic stars is complicated by the necessity of considering the radiant transport in the expanding cloud of a hot optically thick plasma.

Another possible source of gamma rays in collapse of stars is the absorption of neutrinos in the surface layers of a compressed star.[66,75] The main part of the energy released in collapse of stars goes into neutrinos (up to 10^{53} ergs for a mass of the order of several solar masses). Nevertheless, the fraction of energy released in a stellar surface layer optically thin for gamma radiation is small,[66] and this phenomenon cannot be responsible for the observed gamma bursts. The nonlinear interaction of neutrinos and antineutrinos in the vicinity of a collapsing star, which leads to formation of electron-positron pairs and their subsequent annihilation, will lead to a significantly greater energy release,[76] but it turns out to be insufficient to explain the observed gamma bursts.

The authors of the present review have advanced the hypothesis that gamma bursts can arise in the collapse of magnetic stars with $M \sim 10^5\ M_\odot$.[77-79] Numerous observational data[80] now favor the existence of such supermassive stars in the nuclei of active galaxies. The magnetic field of these stars should be very weak: The magnetic energy of a star is equal in order of magnitude to its gravitational energy.[81] In the process of its evolution, a supermassive star radiates energy into the surrounding space, which leads to its compression. The most probable origin of the evolution of a supermassive star is its relativistic collapse. In this case outside a supermassive star an electric field is induced which accelerates the particles of the surrounding plasma to relativistic energies. The electrons accelerated in this way radiate hard gamma rays of synchrotron radiation. The amount of gamma radiation is maximal as the star approaches the process of compression to its gravitational radius.

As a consequence of the small size of the region of radiation and the high density of photons, the hard gamma rays are absorbed in the processes $\gamma + \gamma \rightarrow e^+ + e^-$ and $\gamma + e^\pm \rightarrow 2e^\pm + e^\mp$. As a result there is formed around the collapsing star with $M \sim 10^5\ M_\odot$ an optically thick cloud with dimensions $\sim 10^{11}$ cm consisting of equilibrium electromagnetic radiation which is in local thermodynamic equilibrium with electron-positron pairs. The surface temperature of the cloud T_S is determined by the condition of transparency with respect to the Compton effect for an equilibrium concentration of electron-positron pairs. Calculations show that the surface temperature varies weakly with change of thickness of the radiating layer and lies in the range $(2-3) \times 10^8$ °K.

The total energy release of the cloud is

$$Q \sim 4\pi\sigma R_r^2 T_s^4 \Delta t, \tag{8}$$

where $\sigma = 5.67 \times 10^{-5}$ erg/cm^2-sec-deg^4 is the Stefan-Boltzmann constant, R_r is the size of the radiating cloud, and Δt is the duration of the flare. For $R_r \sim 10^{11}$ cm and $\Delta t \sim R_r/c$ we obtain $Q \sim 10^{52}-10^{53}$ ergs.

The cloud of equilibrium radiation should expand with a relativistic velocity, which will lead to a change of the spectrum and duration of the burst, namely: The characteristic energy of the photons should increase by a factor γ_S, where γ_S is the Lorentz factor of the radiating surface, and the duration of the burst should decrease by a factor γ_S^2. Estimates show that $\gamma_S \sim 3-10$. Therefore the peak of the spectrum should occur in the energy region of order 100 keV. The observed fluctuations in intensity of gamma bursts with duration of the order of tens of milliseconds can be explained by the asphericity of the expansion and the presence of several expanding clouds being formed at different neutral points of the field of the collapsing star.

In terms of this model, the average distance to the sources of observed gamma bursts is of the order of the photometric radius of the Metagalaxy, $\sim 10^{28}$ cm for a Hubble constant H = 75 km/sec-Mpc. For an energy release of $10^{52}-10^{53}$ ergs, the energy flux during the pulse will correspond to the observed value.

The principal observational test of a model is measurement of the dependence of the number of bursts on the flux. The sensitivity of the satellites of the Vela system is sufficient for observation of a significant part of all collapses of supermassive stars occurring in the Universe. Therefore the number of observed gamma bursts should reach saturation, with increase of the detector sensitivity, at a gamma burst frequency of $\sim 10-10^3$ bursts per year in the celestial sphere [79,82] and should not change with further increase of sensitivity.

4. PROMISE OF FURTHER RESEARCH ON GAMMA BURSTS

The diverse hypotheses advanced for interpretation of gamma bursts reflect in some degree the uncertainty of the experimental situation. The existing observational data do not permit identification of sources of gamma bursts with a definite class of cosmic objects. This fact poses the main problems confronting observers in the near future.

Identification of gamma burst sources with some class of astrophysical objects can be achieved either by direct identification of gamma bursts with known optical, radio, or x-ray sources, or by indirect identification obtained by means of statistical methods.

Direct identification of the source of a gamma burst, based only on observations of the bursts, requires extremely high accuracy in determination of the celestial coordinates. Experience shows that for successful identification of x-ray sources with optical objects it is necessary to achieve an accuracy in determination of the coordinates better than one minute of arc. The current state of gamma astronomy permits this accuracy to be obtained only with simultaneous observations of gamma bursts with instruments separated by a distance of the order of an astronomical unit ($\sim 1.5 \times 10^{13}$ cm). The possibility of carrying out observations of gamma bursts in instruments placed on automatic interplanetary stations and permitting determination of the coordinates of the gamma bursts with an accuracy of 0.1–1 min of arc is being discussed at the Goddard Space Flight Center of NASA. [83]

Sources of gamma bursts could be identified with cosmic objects even with less accurate determination of the coordinates. This is achieved by means of correlated observations in several regions (the x-ray sources Cygnus X-1 and Cygnus X-3 were identified in this way). This method encounters great difficulties as the result of the low frequency of appearance of gamma bursts. Nevertheless, excellent possibilities can become available here if an increase of one hundred times can be achieved in the sensity of correlated optical observations with a view of the entire visible hemisphere. [43]

Identification of gamma burst sources with a definite class of astrophysical objects can be achieved also by the method of statistical astronomy—study of the distribution of gamma bursts in flux and galactic coordinates. The conclusions drawn from the data of observations which have been made do not have a sufficient statistical reliability. However, an increase in the observational statistics resulting from an increase in the sensitivity of the apparatus would permit important results to be obtained. High-sensitivity searches for gamma bursts will be carried out in the coming years both by means of specialized telescopes for investigation of bursts and by means of general purpose x-ray and gamma telescopes.

At the present time the laboratories of the various countries of the world are developing plans for apparatus which will permit observations of gamma bursts to be carried out with high spectral and time resolution.

The Los Alamos Scientific Laboratory, whose workers discovered gamma bursts, is preparing a new experiment which will supplement the observations carried out in the Vela satellites. [84] This experiment will be carried out in the satellite SOLRAD-HI, which will be put into operation at the beginning of 1975. This satellite will contain two scintillation counters with CsI crystals 38 mm in diameter and 38 mm thick, a logic circuit, and a memory. The apparatus being planned will permit spectral studies to be made of the gamma bursts with a high time resolution, as small as 0.3 msec; the accuracy of matching the satellite clocks to universal time will be 1 msec. A similar device will be installed also in the second satellite of the SOLRAD-HI series. The Los Alamos Scientific Laboratory has also proposed an instrument for study of gamma bursts which could be placed in a small satellite. [85] Accomplishment of this project would permit a significant increase in the sensitivity of apparatus in the search for gamma bursts.

New designs of instruments for study of cosmic gamma bursts are being developed in a number of laboratories. For example, in the Cosmic Research Institute, Academy of Sciences, USSR, and the Physico-technical Institute, Academy of Sciences, USSR, a new technique has been proposed for determination of the coordinates of gamma bursts, based on the anisotropy of the effective area of scintillation counters. [86] We can hope that the performance of new observations in various satellites will permit solution of the problem of the new extraordinary phenomenon—cosmic gamma bursts.

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