SOME TASKS OF OBSERVATIONAL GAMMA-RAY ASTRONOMY IN THE ENERGY RANGE 5–400 GeV

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Abstract. Brief discussion of the necessity to carry out gamma-ray observations in the uninvestigated energy range 5–400 GeV by instrument on the board of space vehicle is given. One of the possible versions of such gamma-telescope is described and some estimations of the possible statistics are made.

1. State of Observations in Gamma-Ray Astronomy

Observations of celestial gamma-radiation cover a wide energy range: from the lowest energies that are still called γ-rays (hundreds of keV) up to approximately 10^{16} eV. In the energy range from 50–70 MeV up to GeV the main information about gamma-radiation was so far obtained with the satellites SAS-2 (Fichtel *et al.*, 1975) and COS-B (Bignami *et al.*, 1982). In the range 10^{12}–10^{16} eV detection of the γ-quanta is performed with ground instruments measuring Čerenkov radiation of extensive air shower (EAS) particles or of charged components of the EAS generated by the primary γ-quanta in the atmosphere (see the Review by Vladimirsky *et al.*, 1985). But up to now there have been no γ-ray experiments in the 4–400 GeV energy range, although this interval is of great interest for solving the problem of the origin of the γ-radiation.

One can describe the energy spectrum of the *diffuse gamma-radiation of the Galaxy* in the energy range from 0.01 MeV up to 3–4 GeV (for galactic latitudes $\pm 10°$) by the function $I(E_\gamma)\,\mathrm{d}E_\gamma = AE_\gamma^{-n}\,\mathrm{d}E_\gamma$ with $n \approx 1.9$ (see Figure 1 and Sacher *et al.*, 1983). According to modern ideas the diffuse γ-radiation of the Galaxy at $E_\gamma > 0.1$ GeV is the result of the decay of π^0-mesons generated by primary cosmic-ray protons and nuclei in the process of their interaction with interstellar gas in the galactic disk. In this case the energy spectrum of the γ-radiation must reflect the proton spectrum and consequently have $n \approx 2.7$. The difference between the observed and expected γ-spectrum shapes in the energy range below 4 GeV is possibly connected with the proximity of this energy region to the threshold of π^0-meson formation and the $E^{-2.7}$ dependence will occur only at higher energies. That can be discovered if one carries out observations in the energy range 1–400 GeV.

It is known that at present about 25 discrete γ-sources have been discovered. Their energy spectra are defined only for the most intense sources or for those having some peculiar characteristics. Let us list some data for 4 of them.

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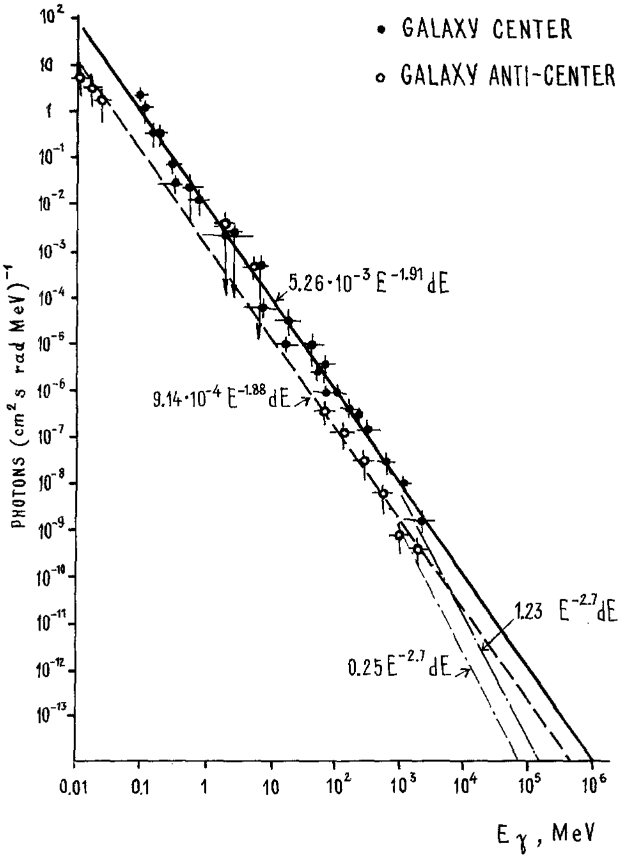

Fig. 1. Differential energy spectra of the diffuse galactic γ-radiation. The experimental points are taken from the review of Sacher *et al.* (1983); the solid and dashed lines are the energy spectra approximations in the form $N(E)\,dE = AE^{-n}\,dE$ for the galactic center ($A = 5.26 \times 10^{-3}$, $n = 1.91$) and the galactic anti-center ($A = 9.14 \times 10^{-4}$, $n = 1.88$). For the energy range $E_\gamma > 1$ GeV the extrapolated spectra are shown for each direction (two cases: $n \approx 1.9$ and $n = 2.7$).

1.1. The sources VELA and CRAB

These are sufficiently well identified with the pulsars PSR 0833 and PSR 0531. Gamma-radiation in the range 70 MeV–2 GeV from these sources was detected very reliably; Vela is the strongest of all γ-sources observed. There are comparatively many data in the energy region $E_\gamma > 10^{12}$ eV for the Crab, but for Vela such measurements are very sparse (Houston *et al.*, 1982). The spectrum exponents for Vela and the Crab in the range 70 MeV to 2 GeV are $n = 1.89$ and $n = 2.2$, respectively (Bignami *et al.*, 1982); at the same time, according to Bhat *et al.* (1987a) the Vela spectrum has the exponent $n = 3.5$ in the region $E_\gamma \approx (3\text{–}10)$ TeV (see Figure 2). Such a difference is an indication of the presence of some spectral peculiarities in the range 2 GeV–1 TeV.

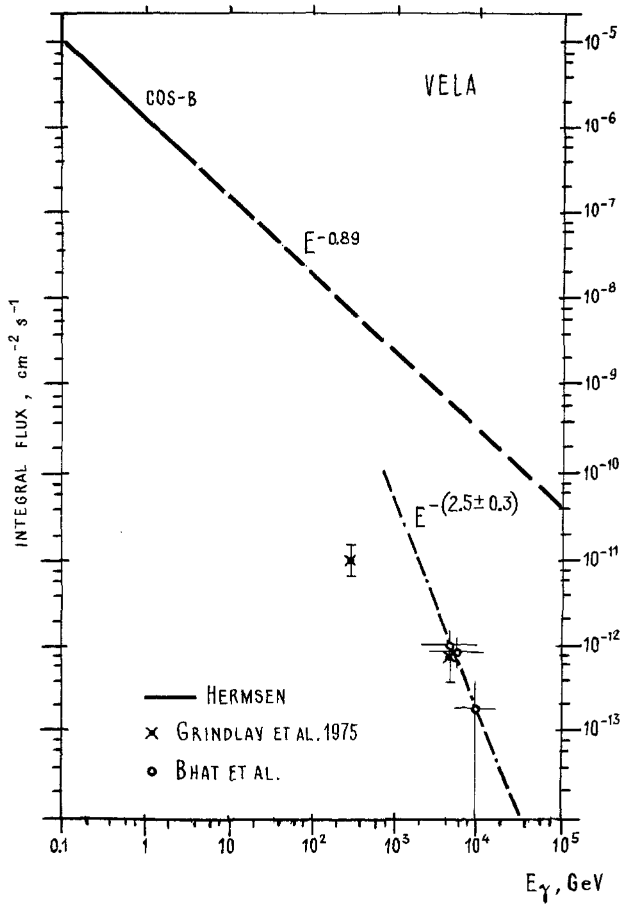

Fig. 2. Integral γ-energy spectrum of the pulsar Vela. Data shown are taken from Hermsen (1980), Grindlay *et al.* (1975), Bhat *et al.* (1987a); the extrapolated spectrum for $E_\gamma > 4$ GeV and one by Bhat *et al.* for $E \approx (4–10)$ TeV are also shown.

1.2. The source GEMINGA (2CG195 + 04)

This is the second in intensity in the energy range 70 MeV–2 GeV. In this range the spectral exponent is $n = 1.8$ (Houston *et al.*, 1982) but at lower energies ($E_\gamma \approx 5–100$ MeV) the radiation of that source is apparently very weak (Glyanenko *et al.*, 1985). A comparison of the measurements in the region $E_\gamma > 10^{12}$ eV with the COS-B data gave $n = 2.3$ (Zyskin *et al.*, 1983, 1985); the results of Kaul *et al.* (1985) are in agreement with this n-value but the measurements of Cawley *et al.* (1985) give for the region $E_\gamma > 400$ GeV an intensity which is 6 times less than one would expect with $n = 2.3$ (Figure 3). There are some conflicting data on the periodic γ-radiation component with the period $T = 60$ s for the Geminga source (Kaul *et al.*, 1985; Buccheri *et al.*, 1985); according to the last data (Bhat *et al.*, 1987b) such a period is not observed and that fact casts doubt on the flux values given by Kaul *et al.* (1985) and Zyskin *et al.* (1983, 1985). Direct measurements in the range 1–400 GeV would clear up the situation.

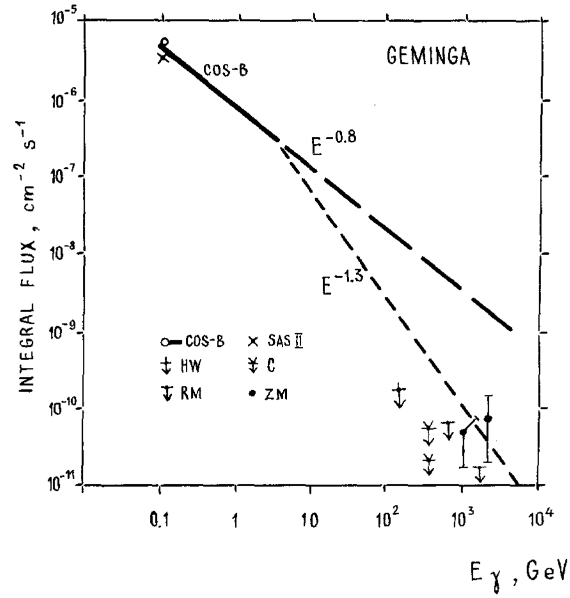

Fig. 3. The integral γ-energy spectrum of the source Geminga. Data shown are taken from the following references: COS-B Hermsen (1980), SAS-II Fichtel *et al.* (1975), HW Helmken *et al.* (1979), C Cawley *et al.* (1985), RM Bhat *et al.* (1987b), ZM Zyskin *et al.* (1983, 1985); the extrapolated spectrum for $E_\gamma > 4$ GeV and one given by Zyskin *et al.* (1983, 1985) are also shown.

1.3. Cyg X-3

This is the variable X-ray source for which one detected γ-radiation both in the range of 0.1–1 GeV and at $E_\gamma > 10^{12}$ eV (Vladimirsky *et al.*, 1985), though some of the data of different authors disagree with each other. For this source the spectral exponent $n = 2$ corresponds to the supposition, that the energy spectrum has the same slope for the very wide energy range from hundreds of MeV up to some TeV.

1.4. Unidentified gamma-sources of the COS-B catalogue

There are some grounds for considering these sources either to be fast pulsars (with millisecond periods) or gigantic molecular clouds (Berezinsky *et al.*, 1984). In the latter case the expected spectrum of the γ-radiation is very gently sloping ($n \approx 1$) down, up to energies of 40 to 100 GeV (Figure 4), with for larger energies a very sharp decrease (Gurevich *et al.*, 1985).

2. Importance of the Range 5–400 GeV

We would like to emphasize that for all gamma-ray sources mentioned above there is no data on the fluxes in the energy range 4–400 GeV but at the same time one has grounds to expect the discovery of some spectral peculiarities exactly in that energy range.

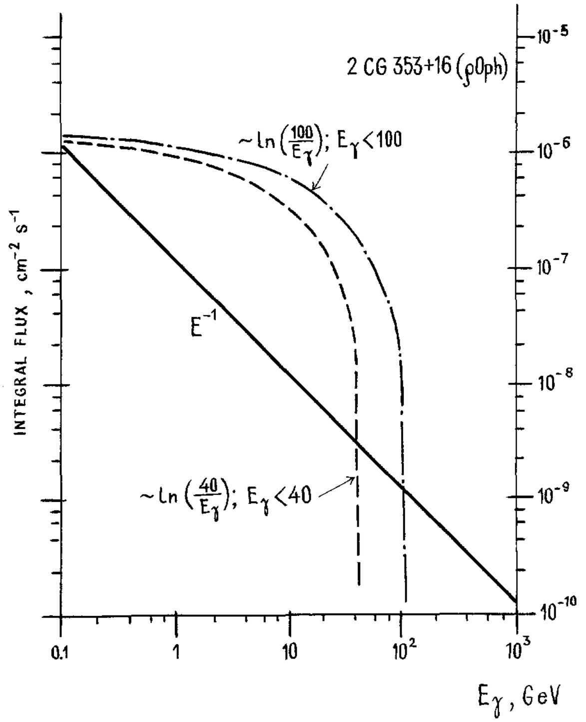

Fig. 4. Assumed integral γ-energy spectra for the source 2CG353 + 16. The three lines correspond to different assumptions for spectral shape (dashed and point-dashed lines correspond to gently sloping spectra with a sharp 'fall' at 40 GeV and at 100 GeV respectively, the solid line corresponds to $E^{-2}\,dE$).

It is readily shown that observations in the γ-ray energy range 1–400 GeV will permit to clear up some questions:

(1) What is the shape of the energy spectrum of the diffuse galactic γ-radiation: does it correspond to the spectrum of the cosmic ray protons or it is not so steep; in the latter case the question of its origin arises – is it perhaps the radiation of unresolved discrete sources?

(2) What is the shape of the γ-ray spectrum of the molecular clouds? Is it true that the observed spectrum corresponds to the proton energy spectrum determined according to modern ideas on the structure of these molecular clouds? On the other hand such observations may allow us to identify some yet unidentified gamma-ray sources with molecular clouds.

(3) What is the shape of the γ-ray spectrum of the pulsar Vela (and possibly of other discrete sources) in the intermediate energy region between $E_\gamma > 1$ GeV and $E_\gamma \sim$ 1–10 TeV where the spectrum is very steep?

Furthermore, direct γ-ray measurements in the energy range up to some hundreds of GeV's for such intense sources as Vela, Geminga and others would give the possibility to 'calibrate' the ground devices, which provide us with information on γ-radiation in the energy region $E_\gamma > 10^{12}$ eV. As is generally known the γ-ray measurements in that interval are made against the very high background of the charged particles and, therefore, the accuracy of the γ-ray flux measurements is small. We would like to emphasize that it is at present impossible to get any information about the fluxes and spectra of the diffuse γ-radiation if one does not carry out direct measurements with instruments on the board of space vehicles.

Let us discuss briefly what the possibilities are of obtaining such measurements with the GAMMA-1 γ-telescope. Is it possible to move further into the region of higher energies (up to 100–400 GeV) with this instrument, actually meant for investigations in the energy range 50 MeV–5 GeV? We shall evaluate the expected number of events which GAMMA-1 can detect during an observation period of 300 hours. In our evaluations we use the following characteristics of GAMMA-1: the sensitive area of the telescope with its axis directed to the source investigated is 1400 cm^2, the detection efficiency for gammas with $E_\gamma > 1$ GeV is 0.2 (Avignon *et al.*, 1986).

TABLE I

Number of gamma counts from discrete sources to be counted by the gamma-telescope GAMMA-1 for 300 hours of observation

Energy E (GeV)	Vela $n = 1.89$		Geminga $n = 2.3$		Geminga $n = 1.8$		Cyg X-3 $n = 2$		Crab $n = 2.2$		Background contribution $n = 1.91$	
	N	N/ST	N	N/ST	N	N/ST	N	N/ST	N	N/ST	N_b	$ST = \sqrt{N_b}$
1	490	27	190	11	190	11	120	6.5	50	2.7	328	18
4	140	14	30	3	60	6	30	3	10	1	92	9.6
10	60	9.5	10	1.5	30	4.5	12	1.9	3	0.5	20	6.4
40	18	5	1.6	0.5	10	3	3	0.9	0.6	0.2	11	3.4
100	8	3.6	0.5	0.25	5	2.4	1.2	0.5	0.2	0.1	5	2.22
400	2.4	2	0.1	0.1	1.6	1.3	0.3	0.2	0.04	0.03	1.4	1.2

The calculated numbers of γ-rays with energy $E > E_\gamma$ are given in Table I for the most intense discrete sources. In these calculations a γ-ray energy spectrum $I(> E_\gamma) = AE_\gamma^{-(n-1)}$ was assumed. The values of A and n were adopted from Bignami *et al.* (1982) for the majority of sources, and from Vladimirsky *et al.* (1985) for Cyg X-3. The results of measurements depend essentially on the contribution of the background to the counting rate of the telescope. There are some grounds to think that the flux of the secondary gammas produced in the surrounding material by cosmic ray particles is small enough at such high energies ($E_\gamma > 1$ GeV) and that the main contribution is given by the celestial γ-radiation. We have made such evaluations for the case of the diffuse γ-radiation from the galactic centre, assuming a spectrum in the form $I^{\text{diff}}(> E_\gamma) = 8.92 \times 10^{-6} E_\gamma^{-0.91}$ quanta m^{-2} s^{-1} rad^{-1}. The number of background gammas to be detected by GAMMA-1 during 300 hr in the case of an acceptance cone with half-angle 2° is given in the last column of Table I. It is seen that from the point of view of statistical reliability one may hope to get some data in the range up to 40–100 GeV for Vela and Geminga if the energy spectrum of the last one is hard enough ($n = 1.8$) and for Cyg X-3 if its intensity and spectral shape correspond to the data given by Vladimirsky *et al.* (1985).

We have evaluated the expected number of detected γ-quanta in the case of a molecular cloud (MC) observation if one assumes (in accordance with the model of Gurevich *et al.*, 1985) that the energy spectra of the γ-radiation has the shape $I(>E_\gamma) = A \ln(E_M/E_\gamma)$ for $E_\gamma < E_M$ and $I(>E_\gamma) = 0$ for $E_\gamma \geq E_M$. The A values were determined on the base of the γ-ray fluxes (for $E_\gamma > 100$ MeV) given by Bignami *et al.* (1982) for the sources 2CG353 + 16, 2CG078 + 01, 2CG288 − 00 which are considered to be molecular clouds. The evaluations were made for the same assumed observational conditions as in the case of the discrete sources (Vela, Geminga, and others), while taking two values for the maximum energy E_M: $E_M^{(1)} = 40$ GeV and $E_M^{(2)} = 100$ GeV (Table II).

TABLE II

Number of gamma counts from the assumed molecular clouds to be counted by the gamma-telescope GAMMA-1 for 300 hours of observation

E (GeV)	2CG353 + 16			2CG078 + 01			2CG288 − 00		
	Gentle spect. with max. E		Expon. spect. $n = 2$	Gentle spect. with max. E		Expon. spect. $n = 2$	Gentle spect. with max. E		Expon. spect. $n = 2$
	40 GeV	100 GeV		40 GeV	100 GeV		40 GeV	100 GeV	
1	180	190	28.5	400	430	65	260	280	41
4	110	130	7.1	250	300	16	160	190	10
10	66	95	2.8	150	220	6.5	96	140	4.1
40	–	40	0.7	–	90	1.6	–	55	1

It appears that the measurements with GAMMA-1 can give a statistically reliable evaluation of the spectra of the most intense γ-sources only for energies < 40 GeV. But as the accuracy of the energy determination decreases at $E_\gamma > 5$ GeV one will not practically succeed in getting with GAMMA-1 reliable results in the energy range discussed (up to hundreds GeV).

3. Proposal of a Special Telescope for 1–400 GeV

It is advisable to create a special telescope for gamma-ray investigations from space in the energy range 1–400 GeV (and maybe for higher energies). Such a telescope, placed in space would allow us to get information about the diffuse γ-radiation and the radiation of the discrete γ-ray sources.

Some proposals for such telescopes have been published (Koch, 1985; Ferrando *et al.*, 1985) some time ago. But we feel it is not useless to discuss some alternative proposals, differing from those proposed earlier by their simplicity and by the better chances of being realized.

Because in the energy range discussed electrons and positrons produced by the convertion of γ-quanta are characterized by small angles of their multiple scattering one has the possibility to design a comparatively simple γ-telescope. It is possible to use thick scintillators for the determination of the electron coordinates (such a device would be considerably simpler than spark or drift chambers used for that purpose in the lower energy range) and to diminish the number of coordinate layers to three, determining the particle's trajectory by three points only. For the same reason one may use a γ-ray converter with thickness of 1–1.5 radiation units (r.u.); it permits one to get a high efficiency in the detection of γ-rays (>50–70%).

A γ-telescope of such a kind may consist of the following main parts: a charged particle separator (anticoincidence scintillation counter); a γ-ray converter; a system of coordinate detectors; the energy measuring device (calorimeter). A scheme of such a γ-telescope, named GAMMA-400, is shown in Figure 5. The cross-section of the coordinate system is a square with sides of 1 m, the distance between top and bottom scintillators of the time-of-flight system (TOF) is also 1 m, the total height of the telescope is about 1.5 m. Such a module has a geometric factor for isotropic radiation of 0.6 m^2 sr and for a linear source of 0.3 m^2 rad.

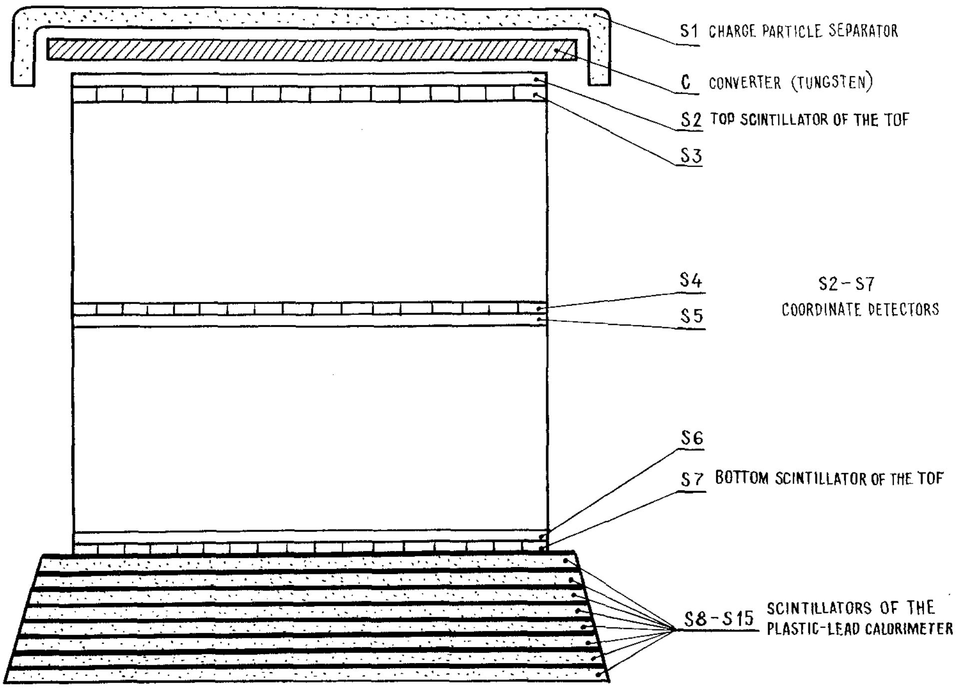

Fig. 5. Scheme of the detecting block of GAMMA-400.

For the coordinate detector, which determines the direction of the primary γ-quanta, one can use a system of trays consisting of a number of scintillation rods. One rod has a length of 1 m and a cross section of 2×2 cm. On each end of the rod there is one photomultiplier, hence the light is collected by two devices. The total number of trays is 6, divided in three layers, each consisting of two trays turned by 90°. So we have the possibility to fix the electron position within cells of 2 cm linear dimension; that corresponds to an angular accuracy of $\pm 1.6°$. In order to determine the electron velocity direction, pulses from the top (S2) and bottom (S7) scintillators of the coordinate system are fed into the TOF circuit. We notice that one may use for the coordinate determination *position-sensitive scintillation* detectors instead of the sectional scintillators discussed above, and in this case the accuracy in the coordinate measurements would increase to 5 mm (an angular accuracy of 0.6°). Such an improvement is connected with some complication of the electronics.

The γ-quanta energy is measured with the lead-scintillation calorimeter which consists of 8 lead layers (with total thickness 22 r.u.) separated one from the other by plastic scintillators (thickness: 1 cm). The accuracy of the energy measurements in the range 1–10 GeV is better than 20%.

The radiator is a tungsten slab of 1 r.u. thickness that gives the possibility to detect γ-quanta with an efficiency not lower than 50%.

The most important part of the instrument is the charge particle separator. As the primary cosmic-ray intensity is 5–6 orders of magnitude higher than the γ-ray value it is necessary for the separator inefficiency for detecting charged particles to stay below 10^{-6}–10^{-7} if one requires that the cosmic ray proton contribution remains below 10% of the γ-ray intensity. Estimates show that a scintillator of 3 cm thickness can provide such an efficiency. Cosmic ray protons may be confused with γ-rays through a re-charge process when proton is converted into a neutron without emitting any fast charge particle which could trigger the anticoincidence scintillator S1. Calculations show that the contribution of this effect at energies $E > 5$ GeV constitutes less than 10–20%. Besides, the shape of the shower in the calorimeter initiated by a nucleon differs from the one initiated by an electron; this circumstance may help us to eliminate the neutron contribution.

One of the possible versions of the electronics is shown in Figure 6. Pulses from all scintillators of the top (S2) and bottom (S7) trays are fed into the input of the Time of Flight (TOF) circuit which selects particles moving from the converter to the calorimeter. The signal produced by the TOF circuit goes to the master formation circuit (MFC), where signals from the separator (S1) and ES circuits are also received. A master signal is formed by the MFC if the signal from the TOF is accompanied by an ES-signal, corresponding to a particle energy exceeding 1 GeV (measured by calorimeter), and not by an S1-signal. The master then opens the way to measure the energy deposited in every layer of the calorimeter and to write down the numbers of the coordinate scintillators through which the charged particles have passed. Simultaneously, the time measurement circuit (TMC) fixes the exact time of the appearance of the event detected, with an accuracy $\lesssim 0.1$ ms. The total information about the event is collected in the intermediate

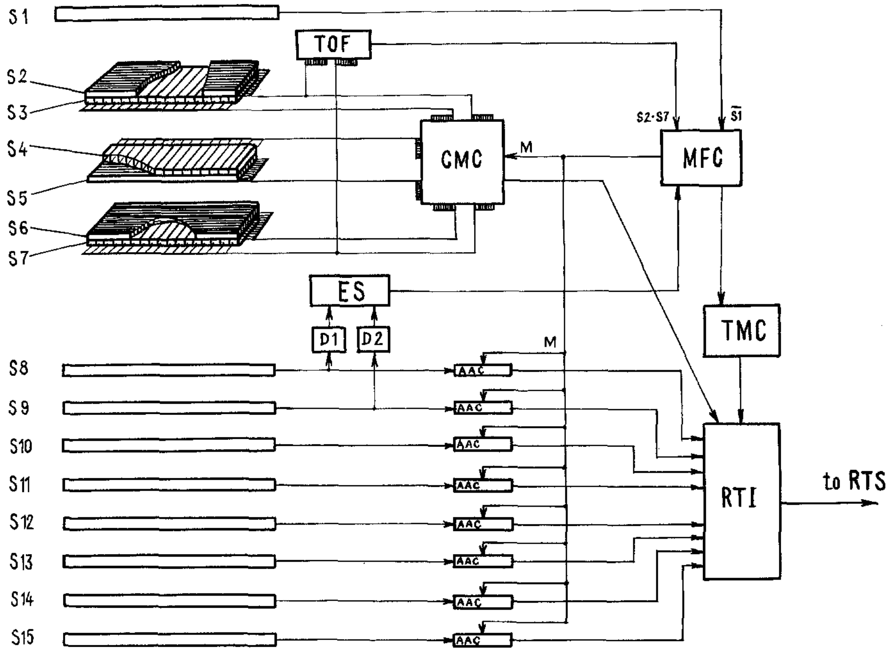

Fig. 6. Block diagram of the GAMMA-400 electronics. S1-S15: scintillators of the detecting block; D1 and D2: discriminators; ES: energy measurement circuit; TOF: time-of-flight circuit; MFC: master formation circuit; M: master signal; CMC: coordinate measurement circuit; TMC: time measurement circuit; AAC: amplitude analyzer circuit; RTI: radio-telemetry interface; RTS: telemetry system.

memory of the radio-telemetry interface (RTI) and is then fed into the telemetry system.

In order to increase the measurement accuracy it is reasonable to use in the experiment not one module but a number of them, which increases the effective area. We have made some estimates of the statistics expected for a time of measurement of 300 hours, and if one uses an instrument consisting of 3 modules. The results are given in Table III for the diffuse galactic γ-radiation, in Table IV for some discrete sources, and in Table V for those objects which are assumed to be molecular clouds. In the case of the diffuse radiation estimate we have taken energy spectra $N(>E) = AE^{-(n-1)}$, n being taken from Sacher *et al.* (1983) in the energy range $E < 1$ GeV; at higher energies we have taken two values for n: one was the same as in the energy range 0.1 MeV–1 GeV and the other was $n = 2.7$ (as the exponent of the proton spectrum). In the last column of Table III we give the calculated count number caused by primary protons if the separator inefficiency is 10^{-6}. In the case of discrete sources (Table IV) we took γ-spectra of the shape $AE^{-(n-1)}$, n being taken from various sources. The last columns of Table IV contain the data on the contribution of the diffuse radiation to the expected counts of the telescope: N_b is the number of counts, and ST is $\sigma = \sqrt{N_b}$. The value N_b was calculated assuming a radius of the source region of 4°, an energy spectrum of the diffuse radiation with $n = 1.9$ and the flux corresponding to the galactic center value. For

TABLE III

Number of gamma counts to be counted by the gamma-telescope GAMMA-400 (3 blocks) in measuring galactic diffuse gamma-radiation for 300 hours of observation

Energy E (GeV)	Direction of the telescope axis				Proton contribution for separator inefficiency 10^{-6}
	At the center of the Galaxy		At the anti-center of the Galaxy		
	$n = 1.91$	$n = 2.7$	$n = 1.89$	$n = 2.7$	
1	48600	28750	16000	5850	2700
4	13760	2720	3200	550	250
10	5980	570	1420	120	54
40	1690	54	410	11	5
100	740	11	180	2.3	1.1
400	210	1.1	53	0.2	0.1
1000	90	0.2	23	0.04	0.02

TABLE IV

Number of gamma counts from discrete sources to be counted by the telescope GAMMA-400 (3 blocks) for 300 hours of observation

Energy E (GeV)	Vela $n = 1.89$	Geminga $n = 2.3$	Geminga $n = 1.8$	Cyg X-3 $n = 2$	Crab $n = 2.2$	Background contribution n = 1.91	
						N_b	$ST = \sqrt{N_b}$
1	37000	14300	14300	9240	3900	3843	62
4	10800	2360	4700	2300	740	1089	33
10	4800	720	2300	900	250	473	22
40	1400	120	750	230	50	134	12
100	600	36	360	90	16	58	8
400	180	6	120	20	3	16	4
1000	80	2	60	9	1	7	2.7

TABLE V

Number of gamma counts from the assumed molecular clouds to be counted by the gamma-telescope GAMMA-400 (3 blocks) for 300 hours of observation

E (GeV)	2CG353 + 16			2CG078 + 01			2CG288 – 00		
	Gentle spect. with max. E		Expon. spect. $n = 2$	Gentle spect. with max. E		Expon. spect. $n = 2$	Gentle spect. with max. E		Expon. spect. $n = 2$
	40 GeV	100 GeV		40 GeV	100 GeV		40 GeV	100 GeV	
1	10990	11860	1780	24920	27000	4050	15960	17310	2590
4	6860	8290	445	15550	18870	1010	9960	12100	650
10	4130	5930	178	9360	13500	405	6000	8650	260
40	–	2360	44	–	5370	100	–	3440	65

molecular clouds (Table V) the spectra were taken as $N(>E) = A \ln(E_M/E)$ for $E < E_M$ and $N(>E) = 0$ for $E \geq E_M$ (in accordance with Gurevich *et al.*, 1985).

The figures in Table III show there is a possibility of measuring the diffuse radiation flux up to an energy of 400 GeV (with a statistical accuracy of 15%) if the spectral exponent is $n = 1.9$ and up to an energy of 40–100 GeV (with an accuracy of 30–40%) if $n = 2.7$. In any case a new and better value for the spectral exponent could be derived.

It appears from Tables IV and V that the measurements described will give the possibility of getting statistically reliable information on the spectral characteristics in the energy range up to 100–400 GeV of several intense discrete sources also including the hypothetical molecular clouds.

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