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A HIGH-SENSITIVITY SEARCH FOR GAMMA-RAY BURSTS BY THE SIGMA TELESCOPE ON BOARD *GRANAT* (THE GALACTIC CENTER AND ALL SKY DATA)

R. SUNYAEV, E. CHURAZOV, M. GILFANOV, O. TEREKHOV, A. DYACHKOV, N. KHAVENSON, V. KOVTUNENKO, AND R. KREMNEV
Space Research Institute, Russian Academy of Sciences, Profsouznaya 84/32, 117810 Moscow, Russia
A. CLARET, F. LEBRUN, A. GOLDWURM, AND J. PAUL
Service d'Astrophysique, Centre d'Etudes Nucleaires de Saclay, 91191 Gif-sur-Yvette Cedex, France
AND
F. PELAEZ, J. L. ATTEIA, P. MANDROU, AND G. VEDRENNE
Centre d'Etude Spatiale des Rayonnements, 9, Avenu du Colonel Roche, BP 4346, 31029 Toulouse Cedex, France
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ABSTRACT

During more than 2 years of the *GRANAT* mission the gamma-ray burst (GRB) cell of the narrow aperture coded mask telescope SIGMA was operating for $\sim$5300 hr. The coding system of SIGMA is capable to localize with arcmin accuracy the GRB events detected through the 18°1 by 16°8 coded vield of view. The sensitivity of the cell to the on-axis events is very high, $\sim 3 \times 10^{-8}$ and 8×10^{-8} ergs cm^{-2} in the 40-90 keV band for 0.25 and 2.0 s of integration time. Nevertheless, no bursts were actually found within the coded field of view. All 18 cosmic GRB candidates detected by SIGMA till now came from the lateral directions i.e., through sidelobes of the sensitivity diagram, having sensitivity at the level of 10% of the on-axis value, but filling a much larger solid angle, than the coded field of view.

For about 950 hr of 5300 the SIGMA was pointed toward the Galactic center (GC), and more than 1.5×10^{10} $M_\odot$ of Galactic matter was each time within the telescope-coded FOV. For the object, placed at 8.5 kpc distance, the threshold burst luminosity in the 40–90 keV band is 3×10^{38} ergs s^{-1}, only slightly exceeding the Eddington limit for the neutron star. The absence of weak GRB events from the GC direction indicates that either the luminosity of typical GRBs is below $\sim 10^{38}$ ergs s^{-1} and GRBs are of local origin, or alternatively luminosity is high $\sim 10^{40}$ ergs s^{-1} or greater and most GRBs come from the massive Galactic "halo" or are of cosmological origin.

Observations of massive extragalactic objects set an upper limit on the frequency of luminous ($\sim 10^{40}$–10^{50} ergs s^{-1}) GRB events from these objects.

The lack of the weak GRB events observed by SIGMA from all directions is hardly consistent with extrapolation of the KONUS data assuming the Euclidean value of 3/2 for the integral GRB counts slope.

Subject headings: Galaxy: center — Galaxy-halo — gamma rays: bursts

1. INTRODUCTION

Gamma-ray burst (GRB) studies by the instruments with sensitivity $\sim 10^{-6}$ ergs cm^{-2} (see reviews of Mazets & Golenetsky 1987; Higdon & Lingenfelter 1990) revealed two important results, hardly consistent with the Galactic neutron stars model of the GRB phenomenon:

1. Up to the achieved sensitivity level the GRB events are isotropically distributed over the sky (Atteia et al. 1987; Mazets & Golenetsky 1987; Higdon & Lingenfelter 1990).

2. The slope of integral GRB counts deviates from the Euclidean value of $-3/2$ well above the sensitivity threshold of the instruments. Although the possible influence of the systematical instrumental effects on this result is still discussed intensively (Mazets & Golenetsky 1987; Jennings 1988; Schmidt et al. 1988; Higdon & Lingenfelter 1990), the lack of weak GRB events is believed to be real. Similar results have been obtained in terms of V/V_{max} and C/C_{min} tests, less sensitive to the instrumental bias (Schmidt et al. 1988; Atteia et al. 1991; Ogasaka et al. 1991).

These results support cosmological or extended Galactic halo models of GRB origin (Fishman 1979; Jennings 1984; Shklovskii & Mitrofanov 1985; Paczynski 1986), although these models also encounter certain difficulties.

On 1989 December 1 the *GRANAT* observatory was launched. The SIGMA coded mask telescope on-board *GRANAT* is aimed to obtain sky images in the 35–1300 keV with 13′ nominal angular resolution (for a detailed description of SIGMA see Paul et al. 1991). The position sensitive detector of SIGMA is equipped with a GRB cell which was operating in almost all observational modes of the telescope. Due to the narrow field of view and effective passive and active shielding of the detector (and therefore low mean background), the GRB cell on-axis sensitivity is at least a few times higher than that of any GRB detectors flown before. Assuming $-3/2$ slope of the integral source counts down to the SIGMA sensitivity it was expected that $\sim$10 weak bursts will be detected by SIGMA each year (and localized precisely!) within $\sim$300 deg^2 (full width at zero response) coded field of view of the telescope. The observations of the Galactic Center (GC) were of particular interest, since in this direction the telescope field of view (FOV) contains $\sim 1.5 \times 10^{10}$ $M_\odot$ that is a notable fraction of the mass of our Galaxy. For the object, placed at GC distance, sensitivity of the GRB cell corresponds to peak 40–90 keV luminosity of the order of Eddington luminosity for 1.4 $M_\odot$ neutron star. Therefore, provided that GRB source density traces general mass distribution in our Galaxy and the typical event has peak luminosity $\sim 10^{38}$–10^{40} ergs s^{-1} above 40 keV, the direction to GC should be distinguished above uniform GRB distribution, observed in previous experiments with lower sensitivity (Mazets & Golenetsky 1987; Hurley 1989; Atteia et al. 1987, 1991).

Reported below are the results of more than 2 years of SIGMA observations. No GRB events have been detected within the coded field of view of the telescope during GC observations as well as during observations of other regions on the celestial sphere.

2. GRB CELL

The GRB cell of SIGMA telescope (Paul et al. 1991; Guerry et al. 1986) has four independent triggers analyzing the detector count rate in two contiguous energy bands with two values of integration time (0.25 and 2 s). The boundaries of the energy bands are adjusted by the telecommands from the ground station and were set at 40–90 and 90–750 keV during the whole observational period reported below. The detection signal is generated provided that the number of photons, detected during the 0.25 or 2 s integration time in any of the two energy bands (40–90 or 90–750 keV) exceeds by 9 standard deviations the background count rate, averaged over the 64 previous seconds. The sensitivity of GRB cell is given in Table 1. Comparison of these values with energy flux from Crab Nebula, measured by SIGMA in 1990–1991 (8.6×10^{-9} ergs s^{-1} cm^{-2} in the 40–90 keV band), shows that quick, within 2 s, turn-on of the source 5 times brighter than Crab (or 14 Crab source within 0.25 s) would activate the GRB cell of SIGMA.

3. SENSITIVITY DIAGRAM

The sensitivity diagram of SIGMA telescope (Figs. 1 and 2) consists of two distinct parts: 18°.1 by 16°.8 rectangular coded region (11°.4 by 10°.5 FWHM) (Fig. 1) and sidelobes with lower sensitivity filling much larger solid angle (Fig. 2). The central 4°.7 by 4°.3 rectangle with constant sensitivity (Fig. 1) corresponds to the fully coded region (the entire detector is illuminated by the source through the coded mask). The remainder of the coded FOV is a partially coded region with decreasing sensitivity (only part of the detector is illuminated by the source through the coded mask). Sensitivity for the sources within the coded FOV can be accurately calculated and calibrated using the observations of well known X-ray sources as Crab, Cyg X-1, etc.

The sidelobes (Fig. 2) with sensitivity at the level of $\sim$10% of the maximum correspond to low absorbing materials between various passive and active shields of the telescope (Lebrun 1991). The calculation of the sidelobes' sensitivity is much more complicated, and should be verified by calibration of spare model of SIGMA on the ground. This work is in progress now in CESR (Toulouse). Nevertheless simple estimates can be done. Since this part of sensitivity diagram will be used below only to obtain upper limits on the GRB counts, certain caution was taken to not overestimate the sensitivity. The sensitivity for bursts coming from the direction with offset angle greater than 90° was ignored for the same reason. Although the sensitivity of the sidelobes is $\sim$10 times less than at the center of FOV, due to a significantly larger solid angle, the total number of bursts expected to come from the sidelobes of sensitivity diagram is larger, than expected from coded FOV.

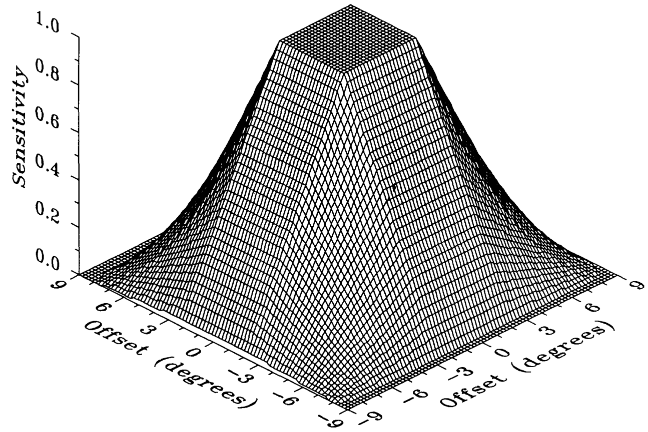

FIG. 1.—Three-dimensional picture of sensitivity diagram of SIGMA coded FOV. Sensitivity is normalized to on-axis value.

TABLE 1

SENSITIVITY OF GRB CELL OF SIGMA TELESCOPE[a]

BAND (keV)	MEAN BACKGROUND (counts s^{-1})	FLUENCE[b]	INTEGRATION TIME 0.25 s	INTEGRATION TIME 2.0 s
40–90	75	F	3.0×10^{-8}	8.6×10^{-8}
		P_{max}	1.2×10^{-7}	4.3×10^{-8}
90–750	300	F	1.4×10^{-7}	4.0×10^{-7}
		P_{max}	5.7×10^{-7}	2.0×10^{-7}

[a] The GRB spectrum was assumed in the form E^{-1} exp $(-E/kT)$ with $kT = 100$ keV.

[b] F: fluence in a given energy band for GRB trigger integration time (ergs cm^{-2}). P_{max}: fluence divided by integration time (ergs cm^{-2} s^{-1})

4. THE POSSIBILITY OF LOCALIZATION OF GRB EVENTS WITHIN CODED FIELD OF VIEW

After the detection signal is generated by GRB cell, coordinates and energies (256 linear channels, covering 35–1300 keV band) of all registered photons and arrival times of each 63d

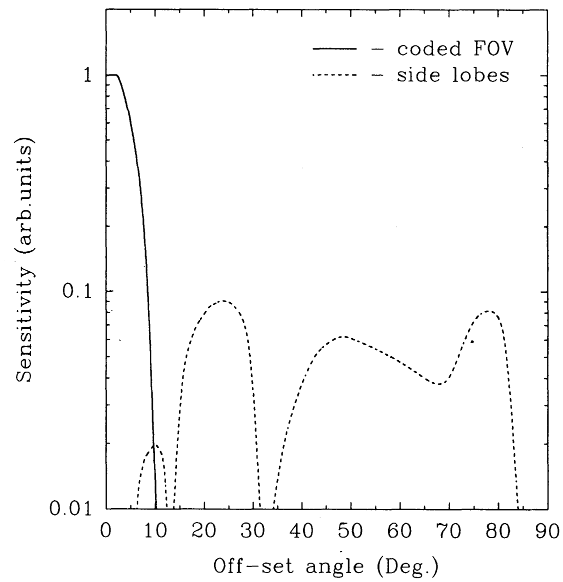

FIG. 2.—Overall sensitivity diagram of SIGMA GRB cell, averaged over rotation angle, as a function of offset from telescope main axis. Solid line corresponds to coded FOV (Fig. 1), dashed line corresponds to sidelobes. Sensitivity is normalized to on-axis value.

photon are recorded. Totally 512 portions of 63 photons are accumulated, of which the first 63 portions correspond to the preburst count rate (duration of one portion ~0.1–0.2 s). These data, combined with imaging capability of SIGMA as a coded mask telescope, give the possibility of precise localization of the γ-ray bursts with the accuracy of $\sim 2'$–$5'$, depending on the brightness of burst. Due to the finite spatial resolution of the detector, the signal-to-noise ratio, obtained on the reconstructed image, is less, than on the total count rate, recorded by the detector. For the sources placed in the fully coded FOV the loss of S/N ratio is maximal and reaches ~2.5 times (in the 40–90 keV band). In the partially coded FOV this effect is less important since only part of the detector, illuminated by the source, is used for image reconstruction while GRB cell analyses the count rate, registered by the entire detector. Thus, the GRB event, ~2 times exceeding the SIGMA sensitivity threshold and located within coded FOV, must be detected on the reconstructed image.

This rapid localization system has been tested and calibrated inflight using GRB-cell triggering by the solar events, occurred during observations of bright sources like Crab and Cyg X-1. Figure 3 shows 69 s image of fully coded FOV, recorded by GRB-localization system during Cyg X-1 observations. The seven standard deviations peak is clearly seen on this image. Obviously, a 6 times brighter source would be detected on the image with the same statistical significance for a 2 s integration time (17 times brighter—for 0.25 s integration time). Taking into account the 40–90 keV energy flux from Cyg X-1, measured by the spectroscopy/imaging system of the SIGMA during the same observation, 1.5×10^{-8} ergs s^{-1} cm^{-2}, it would correspond to an energy flux $\sim 8.7 \times 10^{-8}$ ergs s^{-1} cm^{-2} (2.4×10^{-7} ergs s^{-1} cm^{-2} for 0.25 s)—compare with the values of P_{max} in Table 1. Note, that to trigger the GRB cell, quick (within 2 s) turn-on of the source, 3 times brighter, than Cyg X-1 would be enough.

5. OBSERVATIONS

The overall operating time of GRB-cell on the date of 1992 February 23 is ~5300 hr. For this period the GRB-cell was triggered 136 times. Eighteen of them were tentatively attributed to cosmic GRB (Table 2). The other 118 are either false triggering related to electronic or solar events (Pelaez et al. 1992) or events caused by a charged particle crossing the SIGMA detector.

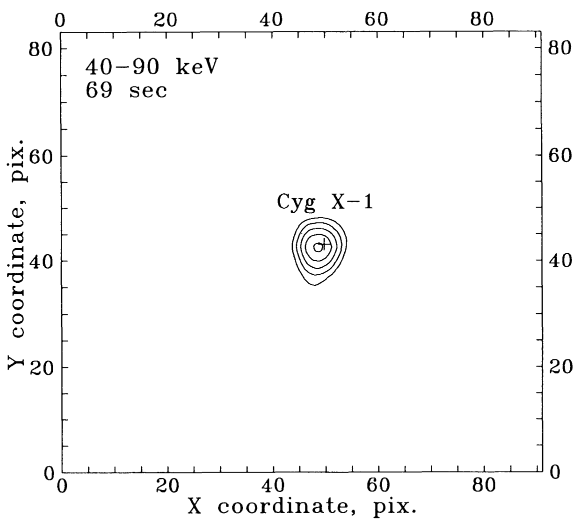

FIG. 3.—Image of fully coded FOV in the 40–90 keV band, recorded by GRB-localization system during Cyg X-1 observations (total exposure 69 s). One pixel corresponds to 3'.3. Contour levels are 3, 4, 5, 6, and 7 s.d. The cross marks the position of Cyg X-1.

TABLE 2

THE LIST OF GRB CANDIDATES DETECTED BY SIGMA

Observation Number	Date	Time (UT) h:m:s
64	1990 Mar 27	10:24:28
66	1990 Apr 04	17:54:35[a]
69	1990 Apr 11	16:41:41[a]
70	1990 Apr 13	03:12:38[a]
87	1990 May 20	12:10:18[a]
96	1990 Jun 04	17:31:33[a]
97	1990 Jun 05	19:23:04[a]
127	1990 Jul 20	21:45:07[a]
177	1990 Oct 14	01:13:21[a]
185	1990 Oct 27	04:21:07[a]
228	1991 Jan 22	15:13:49[a]
273	1991 Apr 17	20:07:32[a]
282	1991 May 17	05:02:44[a]
315	1991 Aug 14	19:14:35[a]
320	1991 Aug 21	10:33:58[a]
363	1991 Oct 26	15:28:49[a]
367	1991 Nov 19	17:12:34[a]
397	1992 Jan 25	08:57:27[a]

[a] The event was also detected by the PHEBUS instrument.

The analysis of recorded images has shown that none of these 18 cosmic events is located within the coded FOV of the telescope. Further confirmation of this result arises from comparison with data of the PHEBUS GRB detector on-board *GRANAT*. All events except for one were simultaneously detected by PHEBUS (for a detailed description of the PHEBUS instrument and results see Barat et al. 1991; Terekhov et al. 1991). SIGMA GRB-cell on-axis sensitivity is at least 3 times higher than PHEBUS sensitivity (recalculated to the 40–90 keV band assuming a power-law spectrum with photon index −2). As a result all events, located within the SIGMA coded FOV and detected simultaneously by PHEBUS, should be clearly seen on the SIGMA burst image, what is not the case. For some events very strong low energy absorption was observed indicating that the photons pass through the shields of the telescope. On the basis of this analysis it was concluded, that no one of 18 cosmic GRB candidates detected by SIGMA was located within 18°.1 by 16°.8 coded FOV of the telescope. Thus, according to Poissonian statistics, an upper limit (3 σ or 99.7% confidence level) of six expected GRB events can be applied to any of the fields observed by SIGMA, as well as to the overall 5300 hr of GRB cell operation time.

6. DISCUSSION

6.1. *The Galactic Center Pointings*

The GC region was observed by SIGMA during 950 hr. Table 3 presents the sensitivity of GRB cell (for a 2 s integration time), expressed in terms of the luminosity of the object, placed at 8.5 kpc distance, assuming thermal spectrum of burst ($1/Ee^{-E/kT}$) with various temperatures. For $kT \sim 100$ keV the threshold luminosity equals $\sim 3 \times 10^{38}$ ergs s^{-1} (40–90 keV) and $\sim 10^{39}$ ergs s^{-1} (bolometric), i.e., it is comparable with the Eddington limit for the neutron star, provided normal cosmic abundances in the emission zone.

TABLE 3

LUMINOSITY OF THE OBJECT, PLACED AT GC DISTANCE (8.5 kpc), CORRESPONDING TO THE GRB-CELL SENSITIVITY[a]

kT (keV)	LUMINOSITY[b]	BAND 40–90 keV	90–750 keV
20	L	3.5×10^{38}	1.0×10^{39}
	L_{bol}	2.9×10^{39}	9.3×10^{40}
50	L	3.5×10^{38}	1.3×10^{39}
	L_{bol}	1.3×10^{39}	7.7×10^{39}
100	L	3.5×10^{38}	1.6×10^{39}
	L_{bol}	1.3×10^{39}	4.0×10^{39}
500	L	3.4×10^{38}	3.2×10^{39}
	L_{bol}	3.9×10^{39}	5.3×10^{39}

[a] For 2.0 s integration time. The GRB spectrum was assumed in the form $E^{-1} \exp(-E/kT)$.

[b] L: luminosity in a given band (ergs s^{-1}). L_{bol}: bolometric luminosity (ergs s^{-1}).

The Galactic center is characterized by the highest mass concentration in our Galaxy. Assuming, that the distribution of GRBs follows the general mass distribution in the Galaxy, the number of Galactic GRB events, expected from the GC direction, should be highest as well. Figure 4 shows the distribution of mass along the line of sight for 9° × 9° FOV (effective size of SIGMA FOV) centered at GC. The peak at 8.5 kpc distance corresponds to the Galactic bulge and contains $\sim 1 \times 10^{10}\ M_\odot$. The Bahcall-Soneira model of the Galaxy was used for this calculation (Bahcall & Soneira 1986). Assuming further that all GRBs have the same intrinsic luminosity and using the all-sky data of the KONUS experiment[1] to obtain the burst rate (per 1 $M_\odot$), it is possible to calculate the number of GRB events to be detected from the GC direction by the instrument with given FOV and sensitivity threshold P_0 (ergs s^{-1} cm^{-2}) (Fig. 5). The intrinsic GRB luminosity L (*bottom axis on Fig. 5*) defines the maximum distance $D = \sqrt{L/4\pi P_0}$ (*top axis*) of the detectable event. The number of bursts is proportional to the burst rate and the mass contained within the cone defined by the FOV and distance D. The sensitivity of SIGMA is $P_0 = 4.3 \times 10^{-8}$ ergs s^{-1} cm^{-2} (Table 1). The burst rate (per 1 $M_\odot$) is defined by the number of events, observed by KONUS from the whole sky and the mass contained within the sphere of radius $D_{KONUS} = \sqrt{L/4\pi P_{KONUS}}$, defined by the intrinsic GRB luminosity L and the KONUS sensitivity (see Fig. 4). One can see that lack of weak GRB events from the GC direction indicates that either the intrinsic 40–90 keV luminosity of typical GRB is below 10^{38} ergs s^{-1} (and GRB are of local origin) or, alternatively, luminosity is high ($\sim 10^{40}$ ergs s^{-1} or greater) and most of the GRBs come from a massive Galactic "halo" (Fishman 1979; Jennings 1984; Shklovskii & Mitrofanov 1985) or are of extragalactic origin (Paczynski 1986; Sunyaev et al. 1992).

6.2. *GRBs from Extragalactic Objects*

Assuming a very high intrinsic luminosity of GRBs $\sim 10^{40}$–10^{50} ergs s^{-1} one could expect the concentration of the bursts toward the massive extragalactic objects as clusters of galaxies or superclusters. Table 4 lists some of the known massive extragalactic objects, observed by SIGMA, and the threshold luminosities of GRB events placed at the distance of these objects. The upper limit (3 σ) of six GRB events can be applied to any of these objects and the upper limit on the rate of bursts with luminosity exceeding the sensitivity threshold can be

[1] According to results of KONUS experiment on Venera 11–14 there are $N(P_{max} > 1 \times 10^{-5}$ ergs s^{-1} $cm^{-2}) \sim 15$ bursts/yr from the whole sky (Mazets & Golenetsky 1987), where P_{max} is the flux above 30 keV. For the thermal spectrum with $kT = 100$ keV, 1×10^{-5} ergs s^{-1} cm^{-2} above 30 keV corresponds to $\sim 3.6 \times 10^{-6}$ ergs s^{-1} cm^{-2} in the 40–90 keV band.

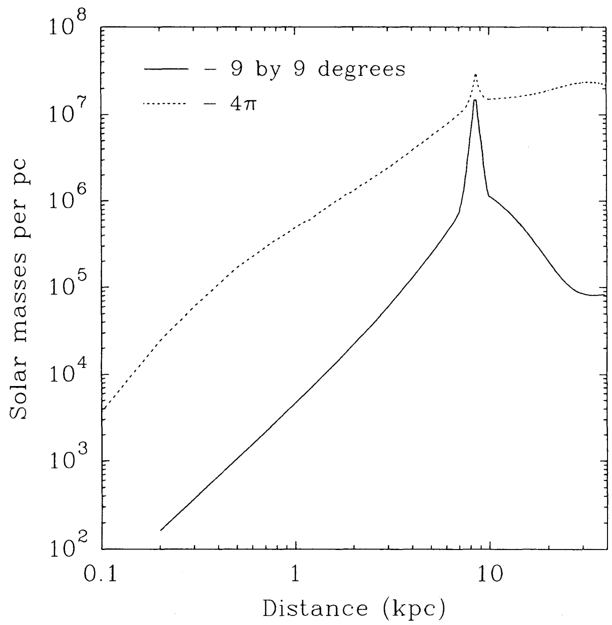

FIG. 4.—Distribution of mass, contained within 9° × 9° FOV centered at GC, along the line of sight (*solid line*). The distribution of mass, averaged over 4π (i.e., as seen by all-sky instruments), is shown by dashed line. The Bahcall-Soneira model of the Galaxy was used (Bahcall & Soneira 1986).

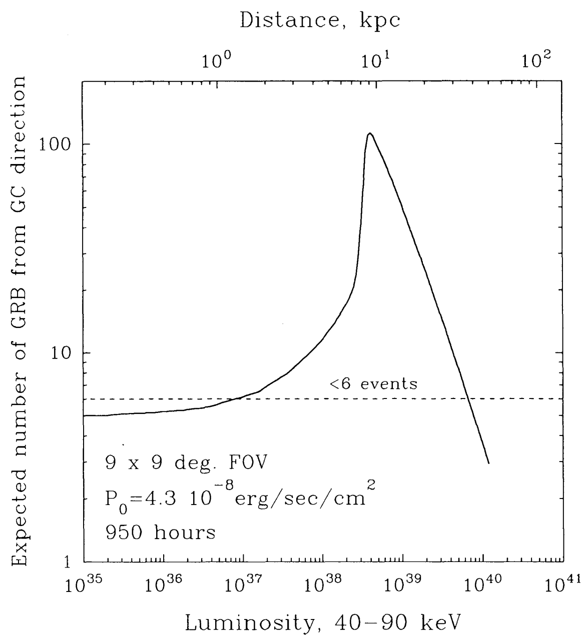

FIG. 5.—Expected number of bursts to be detected by 9° × 9° FOV instrument with sensitivity 4.3×10^{-8} ergs s^{-1} cm^{-2} from the GC direction during 950 hr of observations, plotted as the function of intrinsic GRB luminosity (see discussion for more details). The distribution of the GRB density was assumed to follow general mass distribution in the Galaxy. Horizontal line corresponds to upper limit of six events.

TABLE 4

THE LIST OF MASSIVE EXTRAGALACTIC OBJECTS, OBSERVED BY SIGMA

Object	T (hr)	Distance	Mass[a]	$L_{\mathrm{threshold}}$[b]	Rate[c]
Coma	153	140 Mpc	2×10^{15}	1.0×10^{47}	1.7×10^{-13}
Per X-1	82	110 Mpc	1×10^{15}	6.0×10^{46}	6.5×10^{-13}
M 87	180	22 Mpc	5×10^{13}	2.4×10^{45}	5.9×10^{-12}
LMC	174	55 kpc	8×10^{9}	1.5×10^{40}	3.8×10^{-8}
Cen A	100	5 Mpc	2×10^{12}	1.2×10^{44}	3.3×10^{-10}
GC...........	950	8.5 kpc	1×10^{10}	3.5×10^{38}	5.5×10^{-9}

[a] In solar masses.

[b] In (ergs s^{-1}) for the 40–90 keV flux 4.3×10^{-8} ergs s^{-1} cm^{-2}.

[c] Upper limit on the number of bursts above threshold luminosity per year per solar mass.

derived (Table 4). For the bursts placed at cosmological distances one can use the SIGMA upper limit (six events within ~ 300 deg^2 coded FOV) for 5300 hr of observations in order to restrict the burst rate per unit mass of the universe matter in the same way it was done in previous section.

Another consequence of the cosmological origin of GRB events (intrinsic luminosity $\sim 10^{50}$ ergs s^{-1}) is the correlation of spectral and temporal characteristics of the bursts with the observed intensity: weaker (and therefore more distant) bursts should be longer and softer (for spectra with exponential cutoff at high energies) due to cosmological redshift. For very distant events the bulk luminosity can be shifted from gamma rays to the standard X-ray band, encouraging the search of burstlike events by the high-sensitivity telescopes with normal or grazing incidence mirror systems, like *Einstein*, *ROSAT*, and future programs ASTRO-D, SPECTRUM-X, AXAF, XMM.

6.3. *The All-Sky Data*

Using KONUS results as a reference point for GRB counts and taking into account the SIGMA coded FOV sensitivity diagram (Fig. 1), it is possible to calculate the expected number of GRB events to be detected within coded FOV of SIGMA during 5300 hr of observations as the function of assumed integral counts slope (Fig. 6). It is clear from Figure 6, that only values of slope below 1.2–1.3 are consistent with SIGMA upper limit of six events (3 σ). In particular 15 events would be expected within the coded FOV of SIGMA assuming a Euclidean value of 1.5. Of course, this result can be affected to some extent by the instrumental bias.

Similar procedure can be applied to the whole sensitivity diagram of SIGMA including sidelobes (Fig. 2). Using a lower estimate of sidelobes sensitivity (see above), a lower limit on the expected number of events can be derived (*dash-dotted line in Fig. 6*). The SIGMA data (18 GRB candidates detected during 5300 hr) are consistent with values of integral source counts slope $\sim$0.9–1.0, i.e., notably lower than Euclidean value 1.5, in agreement with recently published results of BATSE (Meegan et al. 1991).

7. SUMMARY

The results of 2 years search for weak GRB events ($\sim 10^{-7}$ ergs cm^{-2}) with SIGMA telescope on-board *GRANAT* are

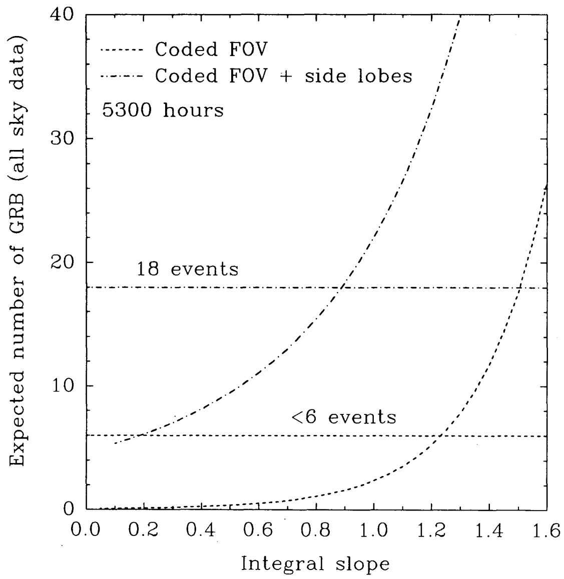

FIG. 6.—Expected number of bursts to be detected by SIGMA during 5300 hr of observations vs. assumed slope of the integral GRB counts. The dashed line corresponds to coded FOV, dash-dotted line corresponds to the overall sensitivity diagram of the instrument (coded FOV + sidelobes). Horizontal lines represent upper limit of six events (3 s.d.) for coded FOV and 18 GRB candidates detected through side lobes.

presented. No GRB events have been detected within the coded field of view of the telescope during GC observations as well as during observations of other regions on the celestial sphere. This result implies the following:

1. The Galactic Center region was not found to be the source of frequent weak GRB with intrinsic luminosity approximately the Eddington limit for a neutron star. This result restricts the rate of bursts with luminosity above the threshold value ($\sim 3.5 \times 10^{38}$ ergs s^{-1} in the 40–90 keV band) originating from the Galactic Bulge to less than $\sim 6 \times 10^{-9}$ bursts yr^{-1} $M_{\odot}^{-1}$. Furthermore, assuming that distribution of GRBs follows mass distribution in our Galaxy, this result prohibits the 10^{38}–10^{40} ergs s^{-1} luminosity range (in the 40–90 keV band) for the typical GRB event.

2. The number of weak GRB events near the SIGMA sensitivity threshold is sufficiently lower than expected from extrapolation (assuming the slope of $-3/2$) of KONUS results (Mazets & Golenetsky 1987). The most steep slope consistent with SIGMA data is ~ 1. Thus, the coded mask instrument with a narrow field of view confirmed the results obtained by previous noncollimated experiments with lower sensitivity (Mazets & Golenetsky 1987; Higdon & Lingenfelter 1990) and the recent BATSE result (Meegan et al. 1991).

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