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Spring, 1997 *GRANAT*/SIGMA observations of the Galactic Center: discovery of the X-ray nova GRS 1737-31

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Abstract. The results of *GRANAT*/SIGMA hard X-ray observations of the Galactic center in March, 1997 are reported. One new source – GRS 1737-31 and two previously known sources – 1E 1740.7-2942 and GRO J1744-28 were detected. The spectral and temporal behavior of GRS 1737-31 suggests that this source may be a distant X-ray Nova and a black hole candidate.

The comparison of the hard X-ray transient detection rates by *GRANAT*/SIGMA and currently operating all-sky monitors (*CGRO*/BATSE, *GRANAT*/WATCH) leads to following conclusions regarding the spatial and luminosity distributions of the hard X-ray transients:

(i) the spatial distribution of X-ray Novae exhibits a concentration towards the Galactic Center similar to the distribution of the visible matter in the Galaxy. In particular, it is more concentrated than Galactic disk population.

(ii) if hard X-ray transients follow distribution of visible mass in the Galaxy then their peak luminosity in the 35–150 keV band is close to 10^{37} erg s^{-1} with a relatively small scatter.

Key words: stars: individual: 1E 1740.7-2942 – stars: individual: GRO J1744-28 – stars: individual: GRS 1737-31 – stars: novae, cataclysmic variables – gamma rays: observations – X-rays: stars

1. Introduction

During Mar. 14–29, 1997 SIGMA telescope has been monitoring the Galactic Center (GC) region. The first observation, carried out on Mar. 14, has revealed the presence of a previously unknown X-ray source, located $\sim 2\fdg4$ from the GC (Fig. 1) (Sunyaev et al. 1997). Few days later the source was also found in the soft X-ray band by *RXTE* and *Beppo*SAX/WFC (Marshall & Smith 1997, Cui et al. 1997*a*, Heise 1997). The hard source spectrum (Sunyaev et al. 1997) and the chaotic variability (Cui et al. 1997*b*) resembled well the properties of X-ray Novae (Sunyaev et al. 1991, Sunyaev et al. 1992) and Cygnus X-1 (Sunyaev & Truemper 1979, Vikhlinin et al. 1994). Basing on the GRS 1737-31 spectral and temporal properties it has been suggested to be a distant X-ray Nova and a black hole candidate (Sunyaev et al. 1997).

The two other sources in the vicinity of the Galactic center, 1E 1740.7-2942 and GRO J1744-28 were detected in the 35–75 keV energy band (Fig. 1) during March 1997 observations (Sunyaev 1997*a*). In this paper we report the results of *GRANAT*/SIGMA observations of the Galactic center in March 1997.

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2. Instrument

The French coded-mask telescope SIGMA (Paul et al. 1991) aboard the Russian *GRANAT* orbital observatory provides arcmin resolution sky images in the 35–1300 keV energy band divided into 95 energy channels. The nominal instrument angular resolution (corresponding to the mask pixel size) is ≈ 15 arcmin. The point source localization accuracy varies from 3–4 arcmin to less than 1 arcmin, depending on the brightness of the source and number of observations. The half-sensitivity boundary of field of view (FOV) is a $11\fdg5 \times 10\fdg9$ rectangle of which a central $4\fdg7 \times 4\fdg3$ corresponds to the fully coded field of view with constant sensitivity. The energy resolution of the instrument at 511 keV is ~ 8%. The typical duration of individual observation is ≈ 20 hours, providing a sensitivity (1σ) of ~ 10–20 mCrab in the 35–150 keV energy domain.

3. 1E 1740.7-2942 and GRO J1744-28

1E 1740.7-2942 was detected by SIGMA in each of the March 1997 observations with average 35–150 keV flux of ~ 90 mCrab (Table 1). The shape of the averaged 1E 1740.7-2942 energy spectrum in 40–300 keV band is typical for this source: it can be approximated by a power law model with a photon index of $\alpha = 2.1 \pm 0.2$ and flux at 100 keV of $F_{100} = (4.7 \pm 0.5) \times 10^{-5}$ phot cm^{-2} s^{-1}) or by an optically thin thermal bremsstrahlung

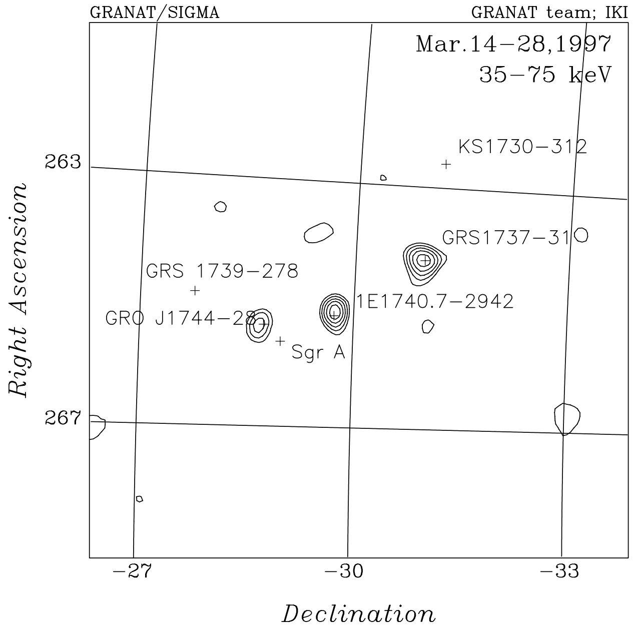

Fig. 1. The 35–75 keV image of the Galactic Center region obtained with SIGMA in March, 1997. Coordinates are for 1950.0 equinox. (contours start at 3σ–level with 1σ spacing)

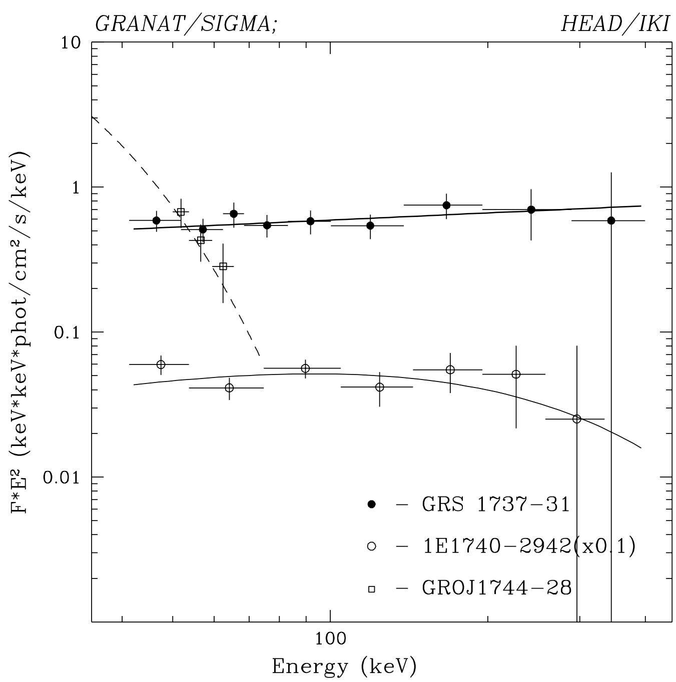

Fig. 2. The energy spectra of GRS1737-31, 1E 1740-292 and GRO J1744-28 (in units of F$\times$E^2) obtained with *GRANAT*/SIGMA during the March 1997 observations. The 1E 1740-292 points were multiplied by 0.1 for clarity.

model ($T = 145^{+70}_{-40}$ keV, $F_{100} = (5.1 \pm 0.5) \times 10^{-5}$ phot cm^{-2} s^{-1}) (Fig. 2). We used these models as convenient simple analytical approximation of the data even if more complex models (e.g. involving comptonization) seem to be more physically justified.

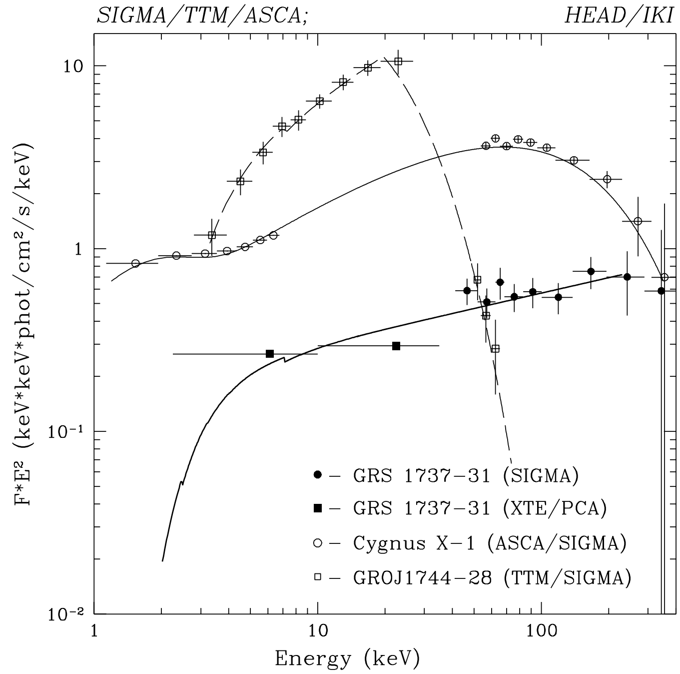

Fig. 3. Broad–band X-ray spectra (in units of F$\times$E^2) of GRS 1737-31 (*filled circles*, SIGMA data; *filled squares*, XTE/PCA data (Marshall et al. 1997)), Cygnus X-1 (*open circles*, ASCA and SIGMA data) and GRO J1744-28 (*open squares*, TTM (Alexandrovich et al. 1997) and SIGMA data).

GRO J1744-28 was detected at an average flux level of 65 mCrab in the 35–75 keV band; as is clearly seen from Table 1, the source flux was highly variable on a ∼week time scale. The 35–75 keV energy spectrum of GRO J1744-28 is very steep with a photon index, $\alpha \sim 5$, which is consistent with a high energy cut – off of the pulsar spectrum at ~ 20 keV (Alexandrovich et al. 1997) (Figs. 3, 2).

No evidence was found for strong activity in the hard X–ray band of the other three sources (GRS 1758–258, GX 1+4 and Terzan 2), which were frequently observed by SIGMA in 1990–1996. The 35–150 flux detected at their positions corresponds to 33 ± 13, 7 ± 11 and -1 ± 8 mCrab respectively.

4. X-ray nova GRS 1737-31

4.1. Position

GRS 1737-31 has been localized by SIGMA with a $\sim 2'$ accuracy (68% error circle radius) at

$R.A. = 17^h36^m50^s, Dec. = -30°58'30''$ (1950 equinox) (Fig. 1).

4.2. Light curve

The flux histories of GRS 1737-31 in the 35–75, 75–150 and 35–150 keV energy bands are shown in Fig. 4. The source has been positively detected for the first time during the Galactic Center region observation started on Mar. 14.3 1997 (Sunyaev et al. 1997). The source flux in the 35–150 keV en-

Table 1. SIGMA March 1997 observations of 1E 1740.7-2942 and GRO J1744-28.

Session	Date, UT	Exposure Time[b] (hours)	Flux, mCrab[a] 35–75 keV	75–150 keV	35–150 keV
			1E 1740.7-2942		
935	14.31–15.67	22.78	141 ± 27	133 ± 33	138 ± 21
937	18.68–19.65	19.42	82 ± 23	66 ± 30	75 ± 18
938	19.80–20.69	17.90	87 ± 24	95 ± 31	90 ± 19
939	22.47–23.59	21.99	111 ± 22	72 ± 28	95 ± 17
940	23.71–24.71	12.00	104 ± 29	102 ± 38	103 ± 23
941	26.50–27.61	22.14	64 ± 22	90 ± 28	75 ± 17
942	27.73–28.63	17.99	40 ± 24	60 ± 31	50 ± 19
			GRO J1744-28		
935	14.31–15.67	22.78	86 ± 27	38 ± 33	57 ± 21
937	18.68–19.65	19.42	102 ± 23	< 30	54 ± 18
938	19.80–20.69	17.90	87 ± 24	< 31	< 19
939	22.47–23.59	21.99	38 ± 22	< 28	< 17
940	23.71–24.71	12.00	39 ± 29	< 38	< 23
941	26.50–27.61	22.14	72 ± 22	55 ± 28	65 ± 17
942	27.73–28.63	17.99	37 ± 24	60 ± 31	46 ± 19

[a] 1 mCrab corresponds to $\sim 1.08 \times 10^{-4}$, $\sim 4.4 \times 10^{-5}$ and $\sim 1.52 \times 10^{-4}$ photons/s/cm^2 ($\sim 8.6 \times 10^{-12}$, $\sim 7.3 \times 10^{-12}$ and $\sim 1.59 \times 10^{-11}$ ergs/s/cm^2) for the 35–75 keV, 75–150 kev and 35–150 keV band respectively
[b] exposure time without dead time correction (typical dead time fraction is $\sim 20\%$)

Table 2. SIGMA observations of GRS 1737-31 during its flare in March 1997.

Session	Date, UT	Exposure Time[b] (hours)	Flux, mCrab[a] 35–75 keV	75–150 keV	35–150 keV
935	14.31–15.67	22.78	76 ± 27	97 ± 33	85 ± 21
937	18.68–19.65	19.42	110 ± 23	121 ± 30	114 ± 18
938	19.80–20.69	17.90	95 ± 24	133 ± 31	111 ± 19
939	22.47–23.59	21.99	65 ± 22	126 ± 28	90 ± 17
940	23.71–24.71	12.00	92 ± 29	137 ± 38	111 ± 23
941	26.50–27.61	22.14	109 ± 22	120 ± 28	114 ± 17
942	27.73–28.63	17.99	99 ± 24	108 ± 31	103 ± 19

[a] 1 mCrab corresponds to $\sim 1.08 \times 10^{-4}$, $\sim 4.4 \times 10^{-5}$ and $\sim 1.52 \times 10^{-4}$ photons/s/cm^2 ($\sim 8.6 \times 10^{-12}$, $\sim 7.3 \times 10^{-12}$ and $\sim 1.59 \times 10^{-11}$ ergs/s/cm^2) for the 35–75 keV, 75–150 kev and 35–150 keV band respectively
[b] exposure time without dead time correction (typical dead time fraction is $\sim 20\%$)

ergy range was practically at the same level of ~ 100 mCrab during all March, 1997 observations (Table 2; Fig. 4).

According to the *XTE*/PCA data (Marshall & Smith 1997) an outburst of GRS 1737-31 in the standard X-ray band (2–10 keV) began between Feb. 17.0 and Feb. 20.4 and peaked at about 25 mCrab – level ~ 2 weeks later. The peak of the soft X-ray luminosity was followed by a smooth decrease on a $\sim$ month time scale (Cui et al. 1997*b*).

Since the GRS 1737-31 position is close to the Galactic Center, it was within SIGMA field of view during almost all observations constituting the Galactic Center survey conducted by SIGMA in 1990–1997, which allows us to estimate an upper limit for the hard X-ray flux from the source position prior to the 1997 flare.

We have performed an analysis of the SIGMA data obtained during 1990–1997 Galactic Center survey, in order to verify the possibility of source appearances prior to its March, 1997 outburst. The resulting 3σ upper limit for the 35–150 keV flux from the GRS 1737-31 position was 7.2×10^{-11} erg cm^{-2} s^{-1}. The ROSAT March 16–29, 1991 pointed observation (3233 s exposure) gives an upper limit $\approx 8.9 \times 10^{-14}$ erg cm^{-2} s^{-1} for the source flux in the 0.1–2.4 keV energy range (Boller 1997).

4.3. Spectra

SIGMA observations in 1997 spring revealed the very hard spectrum of the GRS 1737-31 (Sunyaev et al. 1997), similar to the low state spectra of black hole candidates (Fig. 3, 2). The spec-

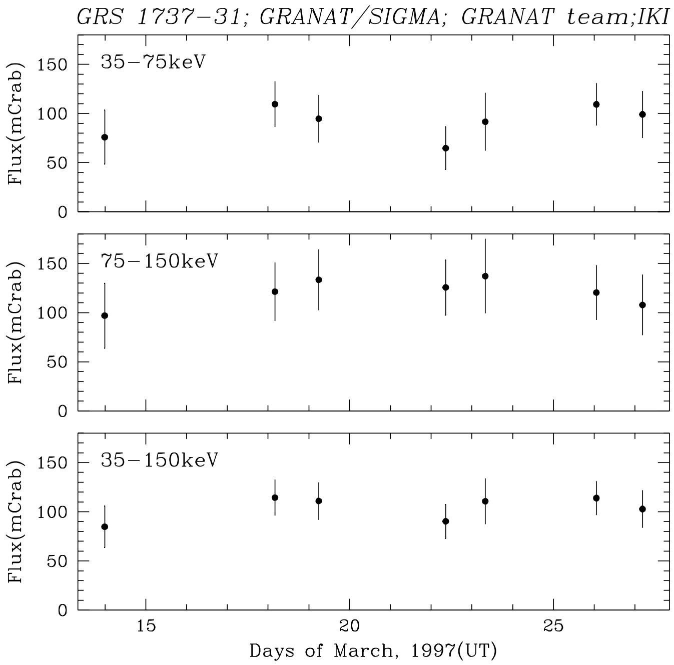

Fig. 4. The lightcurves of GRS 1737-31 in the 35–75, 75–150 and 35–150 keV energy bands in March 1997 (SIGMA data)

Table 3. Parameters of the approximation of GRS 1737-31 average spectrum (40–300 keV band, SIGMA data)

Parameter	
Power law	
Photon index, α	1.83 ± 0.16
F_{100} [a]	5.88 ± 0.47
χ^2(d.o.f.)	53.0(44)
Optically Thick Thermal Bremsstraghlung	
Temperature, keV	230^{+120}_{-60}
F_{100} [a]	6.28 ± 0.50
χ^2(d.o.f.)	54.1(44)

[a] spectral flux at 100 keV, $\times 10^{-5}$ phot cm^{-2} s^{-1}

trum of bursting pulsar GRO J1744-28 is shown for comparison. Drastic difference of spectra in the hard X-ray band is apparent. The 40–300 keV source spectrum (averaged over all SIGMA observations in 1997 March) can be well approximated with a power law model with photon index ~ 1.8 or with a bremsstrahlung model with a temperature ~ 230 keV (Table 3). Unfortunately, the statistical significance of the data is not sufficient to allow us to make a firm conclusion on the source high energy spectral evolution.

Combining SIGMA data with results of the quasi contemporaneous XTE/PCA observations (Cui et al. 1997*a*) the broad band spectral behavior of GRS 1737-31 can be studied. The 2–300 keV energy spectrum of the source has power law shape ($\alpha \sim 1.6$) and does not exhibit soft thermal component (Fig. 4). The measured value of the low energy absorption corresponds to equivalent hydrogen column density (4–6)$\times 10^{22}$ cm^{-2} and is consistent with the location of GRS 1737-31 near the Galactic Center (Cui et al. 1997*a*, Ueda 1997). The character of the source spectral evolution near the maximum of the luminosity is uncertain, since the broad-band spectral observations have begun only ~ 30 days after the source luminosity peak.

5. Discussion

According to the XTE/PCA and XTE/ASM data the GRS 1737-31 light curve in the standard X-ray band is very similar to the light curves of some X-ray Novae. The measured $2 - 300$ keV X-ray luminosity of the source $\sim 2 \times 10^{37}$ erg s^{-1} (assuming the source distance to be ~ 8.5 kpc) is also close to the typical luminosity of the black hole candidates in the *low*(*hard*) state. On the other hand, the quiescent X-ray luminosity of GRS 1737-31 is at least ~ 25 times lower (and perhaps more) than that during the outburst, is another indication of the similarity between this source and X-ray Novae.

5.1. On the spatial and luminosity distribution of hard X-ray transients

Three X-ray Novae (KS/GRS 1730-312, GRS 1739-278 and GRS 1737-31) were discovered with SIGMA during the Galactic Center survey in 1990 – 1997, Spring within a $10° \times 10°$ rectangle (centered on the Galactic Center position and co-oriented with galactic coordinate axes) (Vargas et al. 1996; Vargas et al. 1997; Sunyaev et al. 1997). Assuming an average source outburst duration to be of week to month and taking into account the time coverage factor of SIGMA observations, the rate of appearance of the hard X-ray transients with flux in excess of 100 mCrab in the 35–150 keV energy band (the latter value corresponds to $\sim$ 5–6σ detection during a one day SIGMA observation) within this $10° \times 10°$ area can be estimated as ≥ 1.5 year^{-1}.

The distribution of visible matter in our Galaxy is usually described by the four-component model of Bahcall & Soneira (Bahcall 1986). This model assumes that Galaxy consists of a disk, a spheroid, a central bulge and a massive unseen halo. In Fig. 5 the total stellar mass per unit length per projected area on the sky is shown as a function of the distance from the Earth for different viewing conditions.

As is discussed by Grebenev et al. 1995, the distribution of sources detected with ART–P/*GRANAT* instrument within ~ 5 degrees from the Galactic Center is consistent with the distribution of stellar mass in this region. On the basis the earlier analysis (Skinner 1993) of all known X-ray sources near GC it was suggested that an additional population of sources may be present within $< 1°$ from the GC. However outside the central degree there is no evidence of strong deviations of the distribution of X-ray sources from the distribution of stellar mass (see Fig. 2 in Skinner 1993). We assume below that the hard X-ray Novae spatial distribution follows the stellar mass distribution.

The expected number of new objects to be detected by an instrument with given sensitivity (from given area of sky) de-

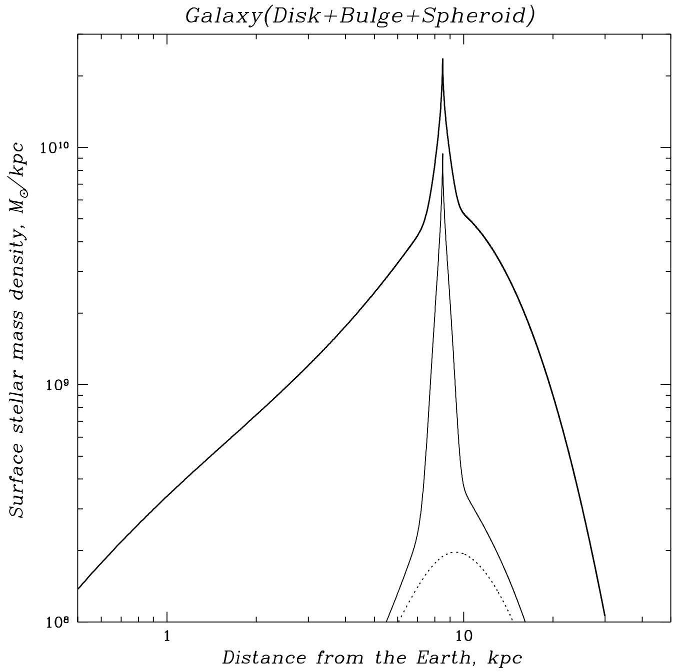

Fig. 5. Galaxy surface stellar mass density (total stellar mass per unit length per projected area on the sky) distribution (Bahcall 1986) as a function of the distance from the Earth under various viewing conditions. The *solid* line corresponds to the all sky observation; the *thin* line corresponds to the observations in a $(10^\circ \times 10^\circ)$ cone centered at the GC position; the *dotted* line corresponds to the observations in a $(10^\circ \times 10^\circ)$ cone centered at the $(l = 20^\circ; b = 0^\circ)$.

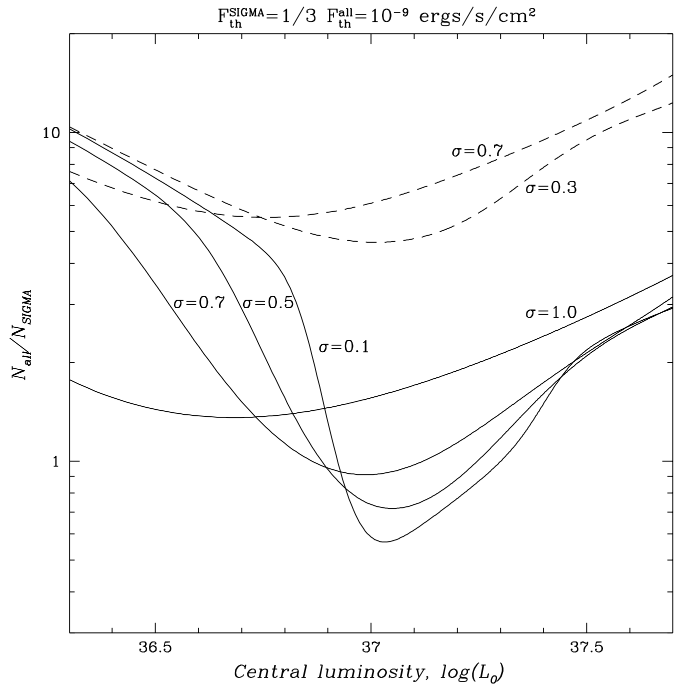

Fig. 6. The expected ratio of transient source detections for $GRANAT$/SIGMA ($10^\circ \times 10^\circ$ cone centered at the GC position) and currently operating all–sky monitors (e.g. BATSE, WATCH), N_{all}/N_{SIGMA} as a function of the central luminosity and width of the transient hard X–ray luminosity Gaussian distribution. The results for the transients distributed according to the Galactic disk and Bahcall & Soneira models are presented by *dashed* and *solid* lines respectively. The new source detection thresholds of SIGMA and all–sky monitors in 35–100 keV energy band were assumed to be $I_S^{th} \sim 100$ mCrab and $I_{all}^{th} \sim 300$ mCrab respectively.

pends on the spatial distribution of sources and their intrinsic luminosity function[1]. SIGMA has a rather high sensitivity of $\sim$ 100 mCrab (5–6σ detection in the 35–150 keV band in a one day observation), but rather narrow field of view ($\sim 17^\circ \times 18^\circ$). Since the number of new transients detected by SIGMA from Galactic Center field is not large (3 sources), we can estimate the expected number of new hard X-ray transient sources on the whole sky with flux e.g. > 300 mCrab in the 35–150 keV energy range in order to constraint spatial distribution and peak luminosity function of these objects. All-sky monitors operating in hard X-rays (like WATCH and BATSE) have a sensitivity (for detection of a new source) close to this value (Sazonov 1997). Taking into account typical duration of the transient outburst ($\approx$ at peak flux) of at least a week or month one can conclude that instruments like BATSE effectively monitor almost the whole sky 100% of time and it is therefore likely that a large fraction of such transients would be discovered.

Thus the all-sky monitors should detect all objects with the luminosity of e.g. 10^{37} erg s^{-1} within ~ 4.3 kpc from the Earth, while SIGMA would detect more distant objects (with the same luminosity), but within a narrow cone. Therefore assuming particular models of spatial distribution and luminosity function one can recalculate the ratio of the expected number of transients which should be seen by all-sky monitors on the whole sky to the number of transients discovered by SIGMA in the Galactic Center field. This is done in Fig. 6. We assumed here that the luminosity function (at peak flux) is described by a Gaussian with a centroid at the 35–150 keV luminosity L_0 and a logarithmic width σ $[\frac{dN}{d(logL)} \sim exp(-\left(\frac{log(L)-log(L_0)}{\sigma}\right)^2)]$. We show in Fig. 6 the expected ratio of number of transients sufficiently bright to be detected by currently operating all-sky monitors to the number of transients detected with SIGMA as a function of L_0. The solid lines correspond to the model of Bahcall & Soneira for the spatial distribution of sources (i.e. we assumed here that distribution of transients follows the visible mass distribution in our Galaxy). The dashed lines correspond to the assumption that transients are present only in the disk component. All curves are labeled with the assumed width of the luminosity function.

As is seen from Fig. 6 the assumption of a broad luminosity function (i.e.large σ) or of a broad spatial distribution without concentration near Galactic Center (e.g. disk) predicts N_{all}/N_{SIGMA} considerably higher than unity. It means that for each transient sufficiently bright to be detected by SIGMA in the GC region (estimated total number of such sources in the GC region for 6 years (1991–1997) observational period after correction on actual SIGMA time coverage is > 9) all-sky mon-

[1] Since we are talking about detection of new (previously unknown) objects, then luminosity function at a peak flux is assumed below.

itors should found more transients on the whole sky. In reality the number of new hard X-ray transients discovered with these instruments during 6 years of almost continuous 1991–1997 observations is equal to 6. One can therefore conclude that (i) the transient sources are more concentrated to the Galactic Center than a pure disk distribution, (ii) if they follow the distribution of visible mass in the Galaxy then their peak luminosity in the 35–150 keV band is close to 10^{37} erg s^{-1} with a rather small scatter (less than factor of ~ 3–4). Note that we are considering luminosity in the hard X-ray band and not the bolometric luminosity.

As it seen from Fig. 5 SIGMA Galactic Center observations allow us to monitor up to $\sim 20\%$ of the Galactic stellar mass (assuming average source 35–150 keV luminosity to be $\sim 10^{37}$ erg s^{-1} and SIGMA source detection threshold to be ~ 50–100 mCrab). Basing on this fact and assuming a direct proportionality between the number of hard X-ray Novae and visible stellar mass, the total rate of the hard X-ray transients in our Galaxy can be estimated to be > 6–7, which is in general agreement with other estimates (White $\&$ Van Paradijs 1997) and recent observations (Remillard 1998).

6. Conclusion

In this section we briefly summarize the results, discussed in previous sections.

Two previously known – 1E 1740.7-2942 and GRO J1744-28 and one new transient source GRS 1737-31 were detected with *GRANAT*/SIGMA during the March 1997 Galactic Center observations.

The spectral and temporal behavior GRS 1737-31 is similar to the one observed for X-ray Novae suggesting that this source may be a distant X-ray Nova and a black hole candidate.

The application of the results of *GRANAT*/SIGMA and currently operating all-sky monitors to the study of hard X-ray transients (hard X-ray Novae) spatial and luminosity distributions leads to following conclusions:

1. the spatial distribution of X-ray Novae exhibits a concentration towards the Galactic Center e.g. like the distribution of visible matter in the Galaxy. In particular it is more concentrated than the Galactic disk population.
2. if hard X-ray transients follow the distribution of visible mass in the Galaxy then their peak luminosity in the 35–150 keV band is close to 10^{37} erg s^{-1} with a relatively small scatter.

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