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NEW OBSERVATIONS WITH THE GAMMA-RAY IMAGER SIGMA

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Since its launch in December 1989, the gamma-ray telescope SIGMA on board the soviet satellite GRANAT works nominally. For the first time a gamma-ray telescope (35 keV - 1.3 MeV) observes the sky with the ability to localise sources with an accuracy of a few arc minutes. Figure 1 presents in galactic coordinates the different sky regions on which the telescope has been pointed since its launch. It can be noticed that a large fraction of the time has been devoted to the central regions of our Galaxy. Figure 2 shows the position of the sources detected by SIGMA in a region of 10° x 10° around the Galactic Center. All these sources exhibit a large variability on all time scales above 35 keV ; these important characteristics revealed by SIGMA must be taken into account for future planned missions.

After a brief description of the SIGMA telescope we will concentrate on some new and exciting results concerning either Galactic and Extragalactic observations.

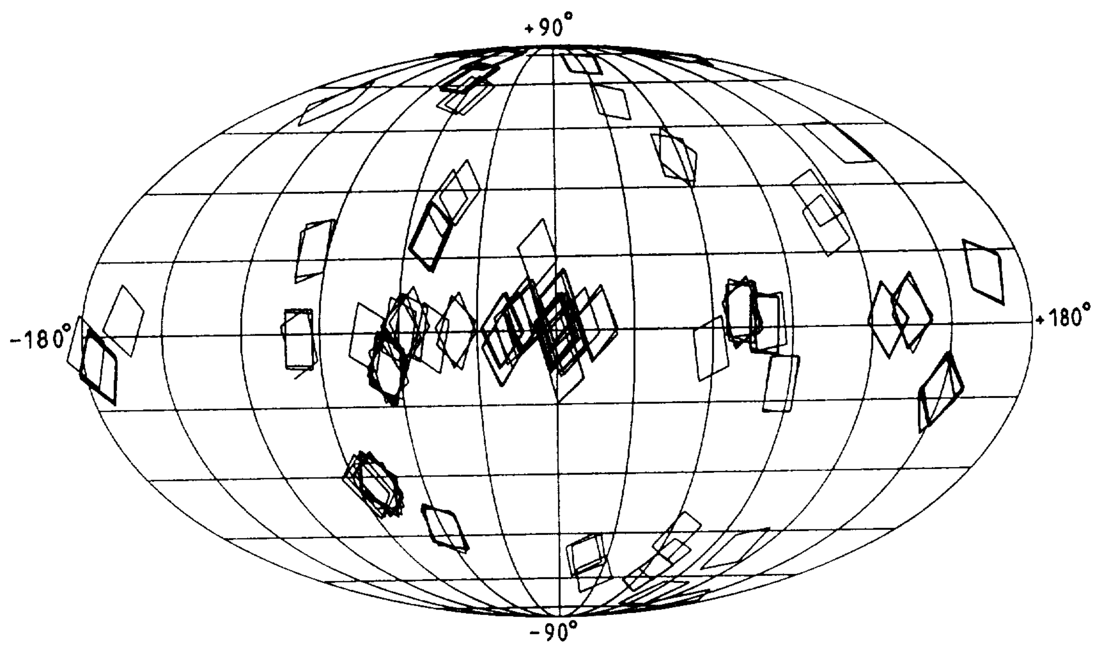

Figure 1 : Sky regions observed by SIGMA, the half sensitivity field of view (11° x 10°) is drawn for each observation.

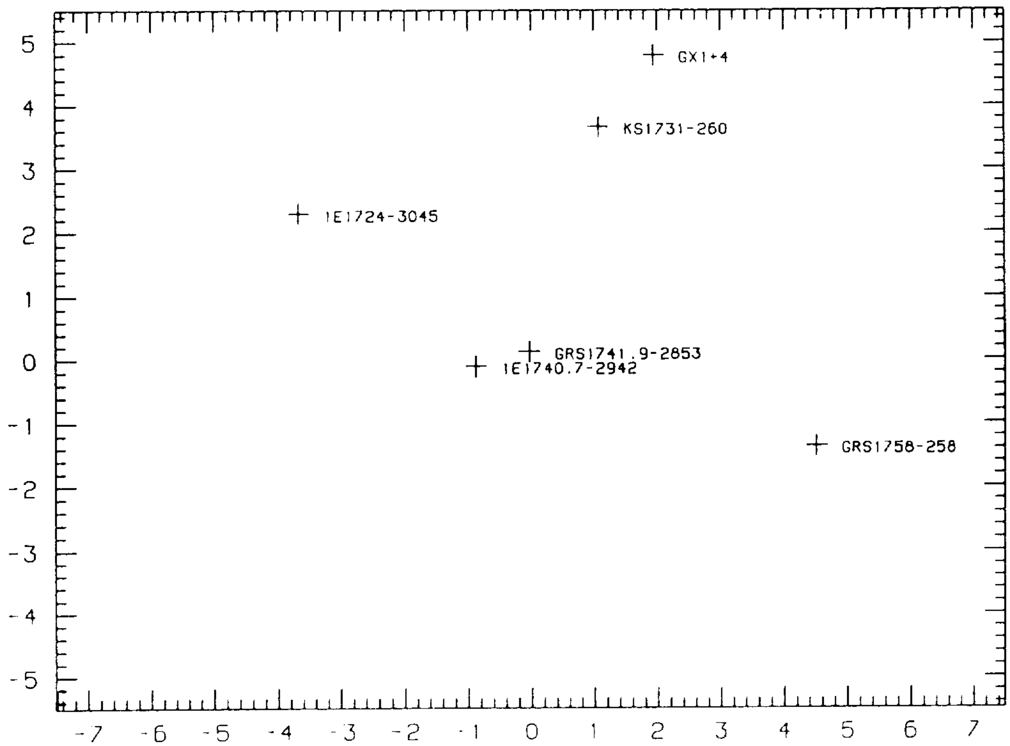

Figure 2 : Galactic center sources observed by SIGMA.

1. Brief description of the SIGMA experiment

SIGMA has been designed by two french laboratories : the Centre d'Etude Spatiale des Rayonnements in Toulouse, and the Service d'Astrophysique in Saclay. It has been realized in the framework of the French-Soviet cooperation under CNES contract and support.

SIGMA operates between 35 keV and 1.3 MeV and provides high resolution images of the sky in this energy range. The imaging capabilities of the instrument are obtained thanks to the association of a coded mask (based on a 31 x 29 URA pattern) and a position sensitive detector (based on the Anger Camera principle). This camera consists of a 1.25 cm thick NaI crystal analyzed by 61 photomultipliers. This detector is surrounded by a large CsI anticoïncidence.

The imaging properties of the instrument are : a 4°45′ x 4°20′ totally coded field of view ; a half sensitivity field of view of 11°20′ x 10°30′ ; a pixel size for high resolution images of 1.6 arc minutes.

A complete description of SIGMA can be found in Ref. 1 .

2. The Galactic Center region

This region was observed by SIGMA in 1990 during 288 hours of useful time. During this period, it has been unambiguously demonstrated that the Einstein source 1E1740.7-2942 is the most luminous object above 40 keV. This object, located 48 arc minutes away from the radiosource Sgr A, was discovered during the Einstein observatory IPC survey of the galactic plane (Ref. 2). Further observations at higher energy (3-30 keV) made with a coded mask imaging instrument (Ref. 3) showed that in this energy range 1E1740 was the strongest source within a 6 x 6 degree square around the Galactic Center.

The hard nature of the source was demonstrated by GRIP (Ref. 31) and by SIGMA during 1990 observations (Ref. 4 and 5). Figure 3 shows the energy spectrum of the source as observed during March/April observations. This spectrum is well fitted by a comptonization disk model (Ref. 6) with an electron temperature KT= 32 keV. In fact during the March, April and September 1990 observations this spectrum remained quite stable. It is interesting to notice that it is almost identical to the CYG X-1 spectrum in low state (Ref. 7).

During the October 13-14 observations of this region a spectacular event occurred : a large bump between 300 and 800 keV appeared in the spectrum of 1E1740.7-2942. This spectral feature, which lasted between 18 and 70 hours, is centered around 500 keV with a clear cut-off close to 700 keV (figure 4).

This shape immediately suggests an electron-positron annihilation process in the vicinity of the source, associated with a hot pair plasma. In the framework of the Ramaty and Mézaros model (Ref. 8). The width of the spectral feature suggests a plasma temperature of 5.10^8 K. The results of the different fits performed on this quite new type of spectrum are given in Table I and discussed in detail in Ref. 9.

Although the bump is not at the same energy, such a structure can be compared to the γ_1 state of Cygnus X-1, but in this precise case a noticeable decrease of the emission under 400 keV has been observed while the spectrum of 1E1740.7-2942 below 200 keV doesn't change.

Very recently Mattesson et al. (1991) reported the same kind of feature (Ref. 10).

During the 1991 observations of the Galactic Center, the picture was drastically different : the observations of Spring 1991 (Ref. 5) showed a decrease by a factor 4 of the 1E1740 flux as well as a change in the spectral shape : the spectral index was $\alpha \approx 3$ (figure 3).

Moreover in the observations performed in August the source was definitely absent from the SIGMA images.

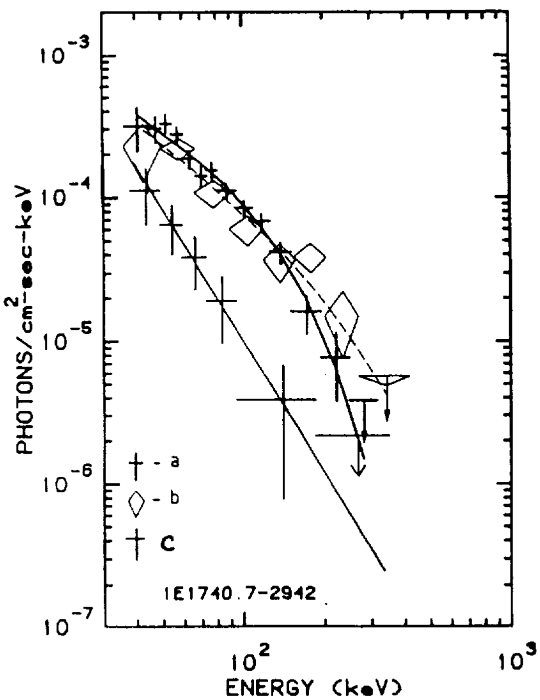

Figure 3 : Spectrum of 1E1740.7 observed in : a) Spring 1990 ; b) October 10th 1990 ; c) Spring 1991

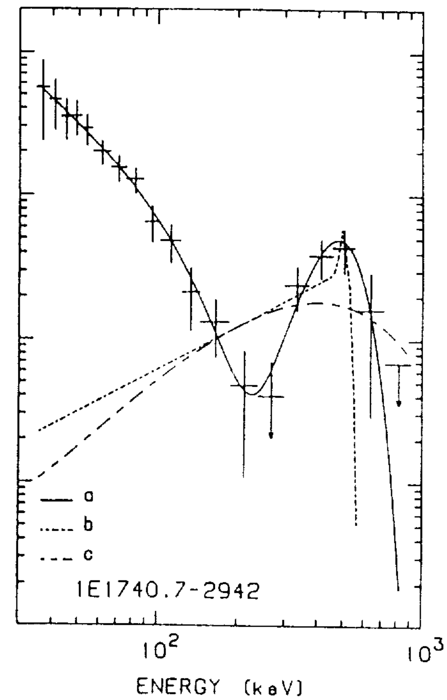

Figure 4 : Spectrum of 1E1740.7 observed on October 13th 1991. The hot pair plasma + comptonization model (a), the positronium model (b), the high temperature comptonization model (c) are reported for comparison.

OCTOBER 13 - 14, 1990					
TWO TEMPERATURE COMPTONIZED DISK		COMPTONIZED DISK PLUS GAUSSIAN LAW		COMPTONIZED DISK PLUS POSITRONIUM	
kT_1 (keV)	20 (+5, -4)	kT (keV)	27 (+8, -7)	kT (keV)	20 (± 3)
τ_1	2.5 (+2.7, -1.0)	τ	1.6 (+1.0, -0.5)	τ	2.5 (± 0.4)
kT_2 (keV)	201 (+139, -72)	Line center (keV)	480 (+96, -72)	Orthopositronium flux (ph/cm^2. s)	0.9 (± 0.3) x 10^{-2}
τ_2	36 (+8, -11)	FHWM (KeV)	240 (+101, -94)	RED $\chi 2$	0.86
RED $\chi 2$	0.90	Flux (ph/cm^2. s)	1.3 x 10^{-2}	degrees of freedom	87
degrees of freedom	85	RED $\chi 2$	0.78		
		degrees of freedom	85		

Table 1 : Model fit parameters for 1E1740.7.

A recent suggestion made by Bally and Leventhal (Ref. 11) explains the variable nature of this gamma emitter : this source can be a black hole situated in a dense molecular cloud (10^5 M_O) which has been observed on the line of sight of 1E1740.7 (see also Ref. 12). The accretion flow might be unsteady providing time variability but can it explain a long extinction of the source as observed last month ?

The 1990 Galactic Center survey by SIGMA led to another important result : the discovery of a new hard source GRS1758-258 (spectral index of ≈ 2) near the position of GX5-1. Its spectrum extends up to 300 keV (Ref. 4).

3. Transient sources observed by SIGMA

GRS 1724-308

Hard X-ray emission at 35-200 keV has been detected in the direction of the globular Cluster Terzan II (Ref. 13 and 14). A possible association with the source X1724-308 has then been proposed.

The observation of X-ray bursts from this source (Ref. 15) indicates the presence of a neutron star. Thus, if this association is real, such a source might be a low mass X-ray binary with a neutron star as the compact object.

In figure 5 are displayed : the spectrum observed by SIGMA, well fitted by a power law of index α = 1.65 (+0.4,-0.6) and the spectrum below 10 keV observed by Exosat in April 1985 (Ref. 16).

Although the variable nature of the source prevents a direct comparison of the two spectra, these observations immediately suggest a two component spectrum.

This transient source might be considered to belong to the class of soft X-ray transients (SFXT) in which we find for example Cen X-4. These transients would be accreting neutron stars in low mass binary systems (Ref. 19).

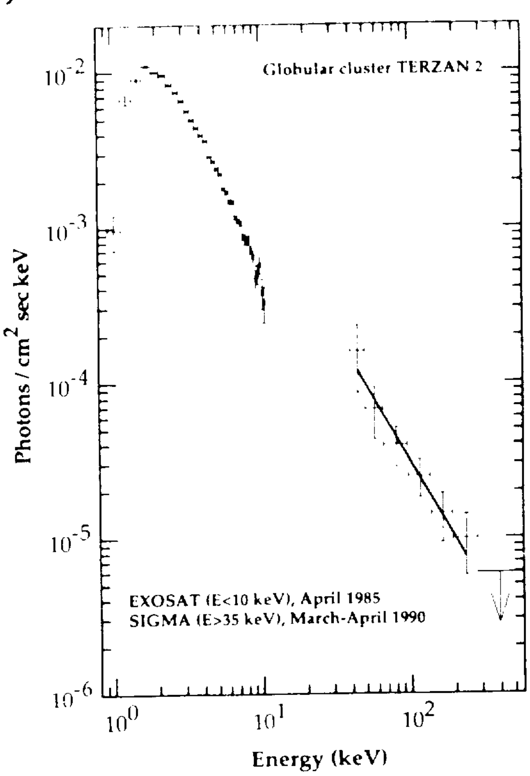

Figure 5 : Spectra of Terzan II region.

Moreover, it is worth noting that a two components spectrum suggested by KS1731 (Ref. 18) and Terzan II observation is quite comparable to the Cen X-4 spectrum measured during May 1979 outburst by the French Signe II MP experiment aboard the Prognoz 7 satellite (Ref. 20). To illustrate this point, the figures 6 and 7 give the light curve of the outburst and the spectra observed at different times during the first peak of this outburst between 13 and 163 keV.

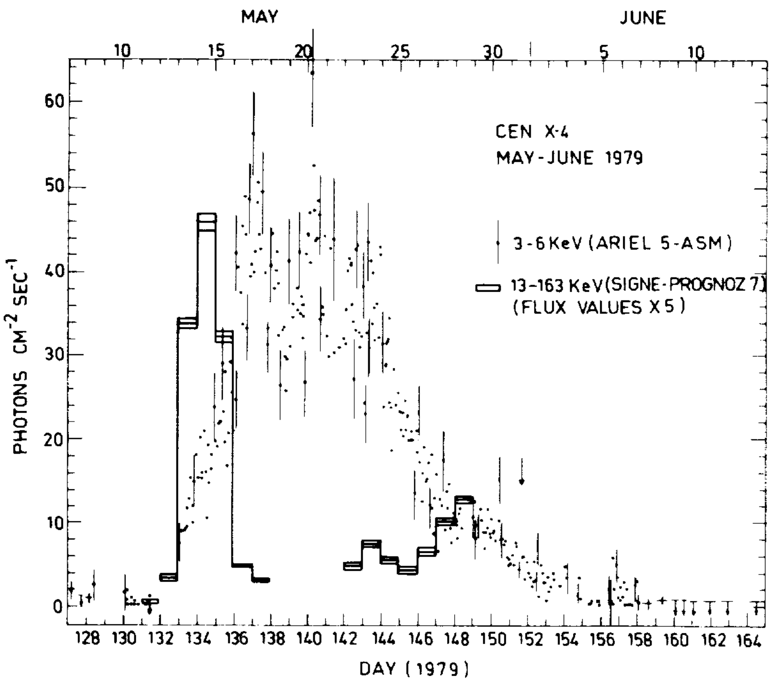

Figure 6 :

Light curve of CEN X-4 as observed by Ariel V and Signe II.

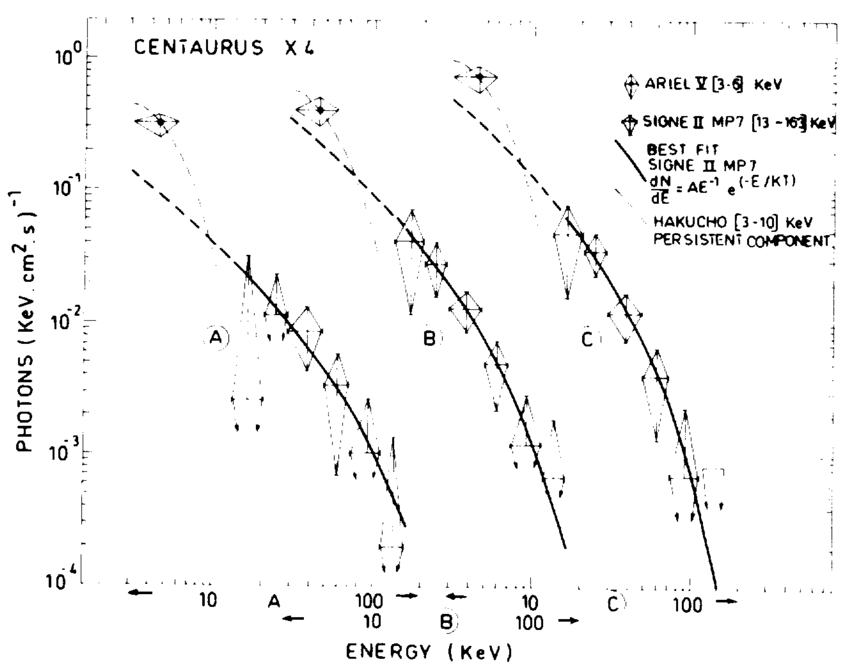

Figure 7 :

CEN X-4 spectra observed during the 1979 outburst.

This idea of possible two component spectra for these transients can be strengthened with another example : the source ASM2000+25 observed by MIR Kvant in the 4-300 keV energy range (Ref. 21). A break in the spectrum is observed between 10-20 keV with a high energy tail above.

Another example of hard X-ray emission for these SFXT is given by the observation on August 1990 of the TRA X-1 transient by SIGMA (IAU Circular no.5104).

Now we will consider the case of Nova Muscae discovered by Watch on Granat and then observed by Ginga and SIGMA. Here we also will find almost the same behaviour.

4. Nova Muscae

A new X-ray nova was discovered in the MUSCA constellation by the Watch X-ray detector and at the same time by GINGA all sky monitor (IAU Circular no. 5161).

The source named GRS 1124-684 was discovered on the 9th February 1991. At this time SIGMA was looking at GX301-2 and the nova was just at the limit of its field of view, despite the low sensitivity of the telescope in this configuration, an image was done showing a great excess compatible with the nova position.

Reorientation of the satellite in the direction of this new source allowed observations on January 16th, 17th, 20th and during five days in February.

During all these observations the source was detected up to at least 300 keV with high significance level. An extensive analysis of these observations can be found in Ref. 22 and 23, while the SIGMA data are reported on IAU circular no.5176, 5201, 5310, 5329.

Figure 8 presents the counting rate in the 41-77 keV energy range for the different observations and Figure 9 shows the evolution of the hardness ratio in the 77-160 keV and 41-77 keV energy ranges. During the first two days it remains stable but after, an anticorrelation appears between the hardness ratio and the counting rate. As it has been observed for the outburst of Cen X-4, the high energy intensity increased and reached a maximum before the low energies ($E_x < 30$ keV) detected for instance by Watch.

Moreover, during the observation of the 20-21st January, the energy spectrum exhibited a clear excess at 480 keV (figure 10). In the same spectrum a strong feature around 170 keV is present. This energy corresponds to the minimum energy obtainable in a single downscattering of 511 keV photons. Even if the line is not observed at 511 keV and is visible only during 13 hours, we should ask the following question : what might be the contribution of such transient sources in the production of lines in the Galaxy ?

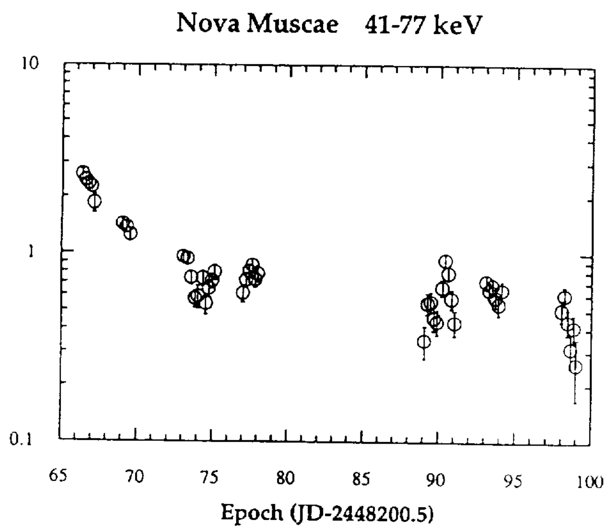

Figure 8 : Light curve of Nova Muscae as observed by SIGMA.

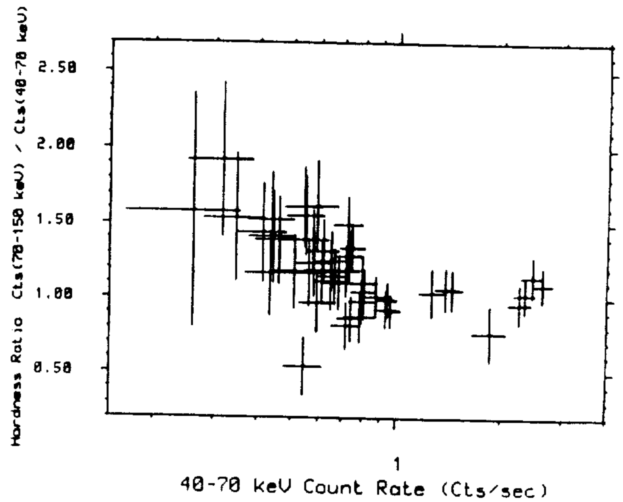

Figure 9 : Evolution of the hardness ratio of Nova Muscae spectrum.

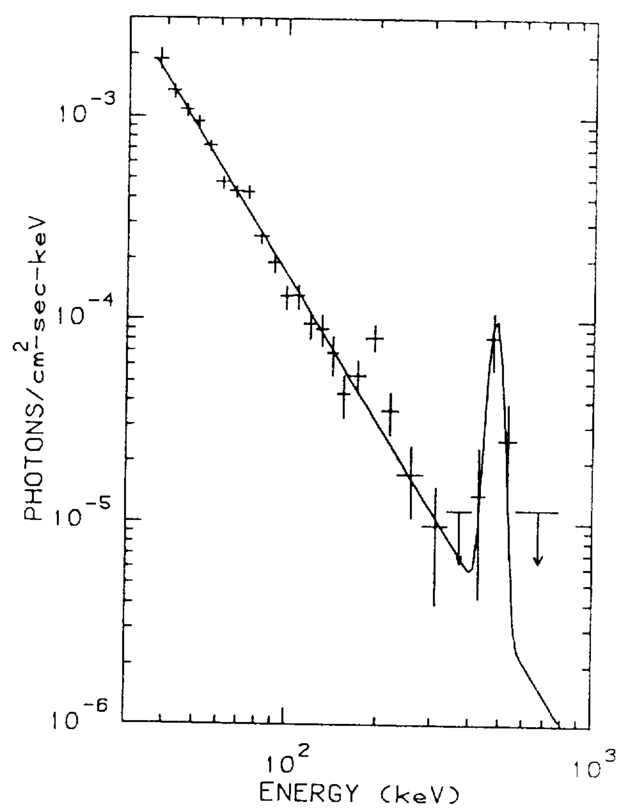

Figure 10 : Spectrum of Nova Muscae, observed during 13 hours on January 20th 1991.

Another point concerns the combined spectrum obtained with Art-P and SIGMA instruments (Ref. 23) : again a break around 10 keV appears clearly putting naturally this object in the class of SFXT as the previous sources reported in this paper.

In fact, even if we have more work to do on the spectral characteristics of these objects, the presence of two component spectra seems to be a common characteristic of SFXTs when they are active at high energy (E > 30 keV).

5. Extragalactic sources

a) NGC4151

This AGN was observed by SIGMA during 82 hours. Figure 11 shows the unambiguous identification at 6σ level (Ref. 24).

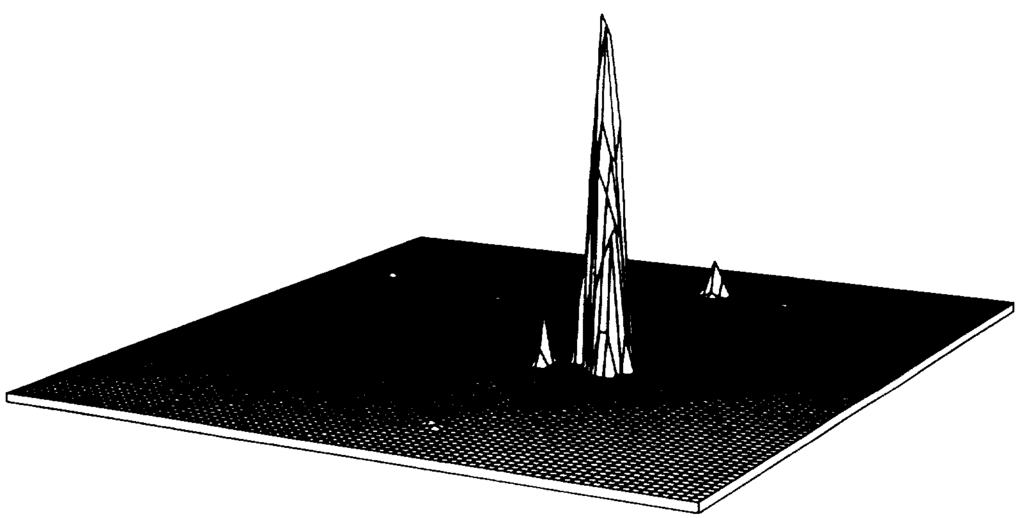

Figure 11 : Map of NGC 4151 region observed by SIGMA. The value below 2.5σ are suppressed.

Figure 12 gives the average photon spectrum obtained combining all the data : it is unusually steep and only marginally compatible with the mean value $\alpha = 0.5$ reported at soft and hard X-ray energies (Ref. 25).

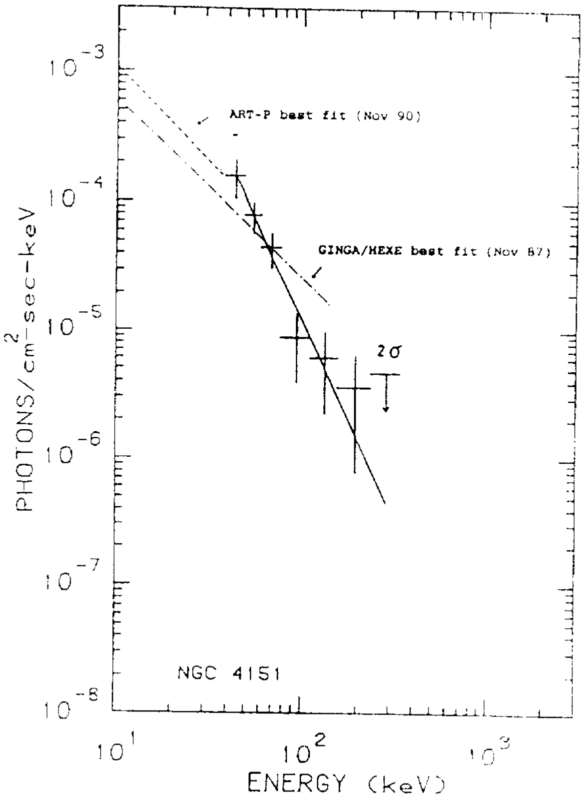

Figure 12 : Spectrum of NGC 4151 in 1990 as observed by SIGMA.

If we consider the Art-P data below 30 keV (Ref. 26) and the SIGMA spectrum a break is visible around 50 keV.

Thus the canonical single power law from a few keV to a few hundred keV is not observable. This kind of spectrum is in good agreement with the observation of NGC4151 made in June 78 by HEAO-A4 (Ref. 27). Even if this spectral behaviour is not permanent and perhaps rare it is worth noting that it is well explained by recent models including compton reprocessing by cold optically thick material very close to the central engine. In fact, first suggested by Guilbert and Rees (Ref. 28), this idea was revived by Zdiadsky et al. (Ref. 29) : γ-rays are absorbed via photon-photon collisions producing non thermal pairs which in turn radiate further X-rays. If a substantial fraction of this radiation interact with cold material, the Compton reflection leads to a composite spectrum which predicts a spectral break around a few tens of keV.

This result on NGC4151 is also interesting for its implications on the contribution of the Seyfert Galaxies to the cosmic diffuse background which also presents a break at 60 keV. If AGNs have steep spectra for some fraction of the time the previous estimate of the AGN contribution to the CDB might have been overestimated at energies greater than 50 keV (Ref. 24).

b) 3C273

A total exposure time of 62 hours cumulating three pointings was devoted to this quasar in 1990 (June, July, November). In the two first pointings the source was clearly detected, the combined spectrum obtained is displayed in figure 13. It is compatible with a power law $\phi_E = (2.4 \pm 0.6)\ 10^{-5} (\frac{E}{100})^{-(1.5 \pm 0.5)}$ ph/cm^2.s.keV (these errors are at 1σ for joint variation of the parameters). The interval between these two observations was 40 days and the 56-120 keV counting rate indicated a variability of a factor 2 at a confidence level of 2.5σ. These data are interesting as they infer a variability on a timescale as short as 40 days.

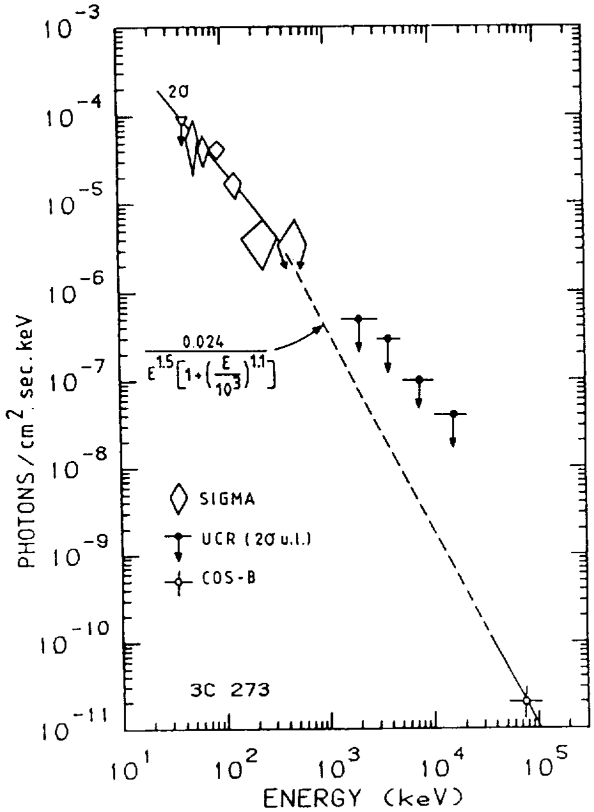

Figure 13 : Spectrum of 3C 273 observed in June/July 1990 observations.

For the observation made in November SIGMA, data show a marginal detection. More details are given in Ref. 30. Another interesting result was also obtained during the November observation of 3C273. SIGMA images revealed a 5.5σ excess in a location (1950) RA = 12h27mn21s Dec = 02°29′12″ with an associated error circle of ± 5′. This source tentatively named GR1227+0229 is situated 15′ away from 3C273 and could explain naturally some strange results on 3C273 : for instance the detection of a half day flare by Ariel V. Even if the presence of the source requires confirmation it clearly demonstrates the need for imaging system in the hard X-ray domain.

Conclusion

This review demonstrates that SIGMA has obtained very exciting results :

- The identification and extensive study of sources contributing to the emission of the Galactic center region above 30 keV.

- The observed strong line at 480 keV from Nova Muscae which may be interpreted as an annihilation line with a redshift due to the presence of a compact object. In this case the contribution of such transients in the 511 keV production should be considered.

- The soft γ-ray tails observed by SIGMA from some transient sources already identified as soft X-ray transients might be a common characteristic of these objects and has to be explained.

- The unusual spectrum of NGC4151 with a break around 50 keV can characterize a particular state of this kind of objects. If it is the case it has interesting implications on the origin of the Cosmic Diffuse Background.

For the near future, as SIGMA works nominally, simultaneous observations of the Galactic Center region with SIGMA and OSSE will be performed. They can be very useful to understand completely the origin of the 511 keV emission from this region ; SIGMA being able to identify the sources which are in hard state during the observations. This is a crucial point, as we have shown that the sources in this region are all highly variable.

This large variability is a common feature clearly demonstrated by SIGMA : if we except the Crab, all sources are variable, some of them disappearing during long periods. Perhaps this large variability is a permanent feature of high energy sources in the soft γ-ray domain. In fact this is not so strange, as a very quiet and common star like the Sun produced recently very high energy gamma-rays during solar flares !

Definitively, such a variability shows the absolute necessity for future missions to associate imaging systems with fine spectroscopic instruments as it is now planned for Integral.

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