OVERVIEW OF THE SIGMA RESULTS

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ABSTRACT

The hard X-ray/soft γ-ray telescope SIGMA is one of the main instruments on board *GRANAT*, the Russian high energy astronomy space observatory, launched in 1989 December. Having examined hundreds of galactic and extragalactic fields during four years of successful in orbit operations, this coded aperture telescope, sensitive to radiation in the energy range 35 keV to 1.3 MeV, has succeeded both in disentangling severe source confusion problems and in providing firm identifications and reliable spectra of sources in such a spectral band. Tens of galactic sources, mainly X-ray binaries harbouring either a black hole (BH) or a neutron star (NS), as well as two isolated pulsars, have been detected up to 1993 December. Suspected BH systems seem to be particularly numerous among the source emitting above 100 keV, including the several X-ray novae so far detected. Bright active galactic nuclei (AGNs) have been detected and monitored during the SIGMA observations, indicating long term (one year time scale) flux variations. Even more interesting is the shorter time scale (few days) variability of these types of object which was observed for the first time at hard X-ray energies. A wealth of SIGMA results has been published so far, and we will summarize here some of the most prominent ones.

1. Introduction

Hard X-ray/soft γ-ray astronomy has long been considered as a particularly arduous field since focusing techniques are totally impracticable above ~ 10 keV, whereas estimating each photon direction by analyzing the pair tracks – as in EGRET [1] – or the geometry of Compton diffusion – as in COMPTEL [2] – does not work below ~ 1 MeV. In between, astronomers have to rely on big collimated scintillator such as OSSE [3]. At the beginning of the previous decade, it was recognized that a possible way to improve existing hard X-ray/soft γ-ray telescopes is the incorporation of the coded aperture technique to actually image celestial sources. The primary advantage of such a technique is to maintain the angular resolution of a single pinhole camera, while increasing the overall effective area of the instrument. Moreover, as the coded mask principle includes the simultaneous measurement of the sky and detector background, systematic effects due to temporal variations in the background are removed. The coded aperture concept had been successfully put to use in the X-rays domain by XRT on *Spacelab 2* [4], and at higher energy by the GRIP balloon borne experiment [5].

This paper reports on four years of successful high angular resolution observations performed by SIGMA, the first coded aperture telescope sensitive to radiation in the energy range from 35 keV to 1.3 MeV to be operated in space. We present here a selection of the salient scientific results obtained so far, with intent to emphasize the unique contribution of the imaging properties of the telescope, which were determinant not only to disentangle severe source confusion problems but also to enable firm identifications of sources. Even in the absence of source confusion problems, because the source is seen on the image and the background is measured at the same time and the same pointing as the source, imaging observations give source spectra which are free from any contamination from the background and/or from other nearby sources.

2. Instrument

The SIGMA telescope, one of the main devices on board the Russian *GRANAT* satellite, successfully launched on 1989 December 1st from Baikonour, Kazakhstan, was constructed by two French laboratories (Service d'Astrophysique at Saclay, and Centre d'Etude Spatiale des Rayonnements at Toulouse), both under contract to the Centre National d'Etudes Spatiales, the French Space Agency. This hard X-ray/soft γ-ray instrument of unprecedented size – weighing about one ton, it measures 3.50 m high and the diameter at the base is 1.20 m – features a coded mask, a position sensitive detector (PSD) whose design is based on the principle of the Anger cameras used in nuclear medicine, active and passive shielding devices, and the needful service modules (for a detailed description, see Paul *et al.* [6]. The key imaging features of the telescope, whose total detection area is the 794 cm^2 central rectangular zone of the PSD matching the basic 29×31 mask pattern, are the intrinsic angular resolution : 13′, and the point source location accuracy, which is less than 2′ for strong sources. Those properties are maintained over a $11.5° \times 10.6°$ field of view (FOV) at half sensitivity and over a $4.7° \times 4.3°$ FOV at full sensitivity.

Since the launch of the satellite into its nominal eccentric 4 day orbit (perigee 2000 km, apogee 200 000 km)[1], four years of in flight operations have been achieved, leading to a precise estimate of the in orbit performances of the instrument and of its long term evolution [7,8]. For broad band observations in a typical 10^5 s exposure, the 3 σ sensitivity of SIGMA is 1.5 10^{-5} photon cm^{-2} s^{-1} keV^{-1} (or 30 mCrab) at 100 keV. Identified spectral features observed from time to time during the mission have been used to confirm the instrument energy resolution as measured at the launch base before the flight : 16% at 60 keV, 12% at 122 keV and 8% at 511 keV. By the end of 1993 December, more than 500 celestial fields have been examined. In most cases, images with pixel size of 1.6′ are accumulated in four contiguous wide energy bands, and images with pixel size of 3.2′ are accumulated in 95 energy channels between 35 keV and 1.3 MeV.

In the usual data analysis procedure, the recorded images are first corrected in order to remove spatial non uniformities which are in part intrinsic to the detector and in part due to a structured background, and the sky images are reconstructed using standard deconvolution techniques. Point sources are located as maxima in the deconvolved images, with peak shape compatible with the SIGMA point spread function. Since the SIGMA telescope can observe in 95 consecutive energy bands, in each of which an image of the sky is derived, It is possible to obtain the count spectrum of a source independently of any other emission which originates from its surrounding, as e.g. from other sources within the FOV and from diffuse processes. As for other devices operating in the soft γ-ray regime, which is dominated by Compton scattering, a precise knowledge of the energy response function of the PSD is required to derive the actual source photon spectrum. Estimates of the SIGMA energy response are based on the ground calibrations performed in the launch base just before the flight, substantiated by the results of a precise Monte-Carlo simulation [9] to interpret the ground measurements.

3. General results

Table 1 presents the list of sources imaged by SIGMA up to 1993 December. The telescope operates in pointing mode only, and has mainly observed the Galactic Plane and particularly the Galactic Center (GC), where its imaging capabilities are best put to use. This list, which is just a compilation of already published positive source detections, is not a true statistical sample at a given sensitivity level. The source celestial coordinates (Equinox 1950.0), as presented in Table 1, have all been derived from the SIGMA data. Only two sources of this list, the Crab and 3C 273 are common to the list of sources so far detected by EGRET at 100 MeV [1]. Indeed, the hard X-ray spectra of the SIGMA sources are often cut off at a few hundred keV, whereas all the EGRET sources (except the Crab and 3C 273) present within the celestial field so far observed by SIGMA, have 100 keV flux below the SIGMA sensitivity limit. This may tell that thermal processes are still at work in the SIGMA range, pure non thermal processing taking over only at MeV energies.

[1] After a brief period of falling (from 2000 km down to 1000 km), the perigee is continuously rising, in such a manner that, from orbit to orbit, the time spent within the active fraction of the radiation belts becomes more and more reduced. Four years after launch, the perigee altitude was > 30 000 km.

TABLE 1

List of sources detected by SIGMA up to 1993 December

Name	$\alpha_{(1950)}$	$\delta_{(1950)}$	Activity	Nature
GRO J0422+32	4 18 29	32.79	Nova	BH system ?
M1/PSR 0531+21	5 31 30	21.98	Stable	Nebula/Fast pulsar
GS 0834-429	8 34 11	-42.94	Transient	Binary X-ray pulsar
GRS 1124-684	11 24 08	-68.38	Nova	BH system
NGC 4151	12 08 00	39.62	Variable	AGN (Seyfert 1)
NGC 4388	12 23 36	12.95	Weakly variable	AGN (Seyfert 2)
3C 273	12 26 40	2.36	Weakly variable	AGN (quasar)
GRS 1227+025	12 27 20	2.50	Transient	?
Cen A	13 22 18	-42.82	Strongly variable	AGN (radio galaxy)
PSR 1509-58	15 10 02	-59.02	Stable	Fast pulsar
TrA X-1	15 24 35	-61.66	Transient	BH system ?
OAO 1657-415	16 56 59	-41.57	Transient	Binary X-ray pulsar
GX 339-4	16 59 00	-48.73	Strongly variable	BH system ?
4U 1700-37	17 00 27	-37.78	Extremely variable	NS system
GRS 1716-249	17 16 34	-24.96	Nova	BH system ?
Terzan 2	17 24 14	-30.74	Variable	?
MXB 1728-34	17 28 45	-33.81	Flaring	X-ray burster
GX 1+4	17 29 02	-24.74	Rapidly variable	Binary X-ray pulsar
KS 1731-260	17 31 12	-26.09	Transient	X-ray burster
Terzan 1	17 32 38	-30.46	Variable	?
GRS 1734-292	17 34 00	-29.20	Transient	?
SLX 1735-269	17 34 58	-26.92	Persistent	?
1E 1740.7-2942	17 40 42	-29.72	Strongly variable	BH system ?
GRS 1741.9-2853	17 42 00	-28.89	Transient	?
A 1742-294	17 42 51	-29.49	Flaring	X-ray burster
GRS 1743-290	17 43 18	-29.05	Strongly variable	?
GRS 1747-341	17 47 26	-34.19	Persistent	?
GRS 1758-258	17 58 08	-25.74	Strongly variable	BH system ?
GRS 1915+105	19 12 51	10.86	Strongly variable	?
Cyg X-1	19 56 26	35.07	Weakly variable	BH system

4. Galactic hard X-ray sources viewed by SIGMA

A large fraction of the SIGMA sources listed in Table I are galactic stellar accreting systems, among which all are variable and many are transient sources, i.e. detectable only a small fraction of the time when in high state. The Crab (nebula and pulsar are not distinguished by SIGMA), which is together with PSR 1509-58 the only source powered by rotation in the list presented in Table 1, is also the only mostly stable source. This extreme variability of the 100 keV sources is a direct consequence of their small size and the violent nature of the processes involved.

4.1. Black hole systems

Persistent sources. The prototype of BH binaries is Cyg X-1, whose spectrum in the normal state is characterized by a power law of index close to -2.0, cut off above 200 keV. Such a spectrum is usually interpreted, following Sunyaev & Titarchuk [10)] as the result of Comptonization of soft ($\leq$ 1 keV) photons by hot (~ 50 keV) electrons. Cyg X-1 was always caught by SIGMA in the same low state [11)], while transient very low frequency (~ 0.04 Hz) quasi periodic oscillations (QPOs) have been discovered by SIGMA [12)]. GX 339-4, also suspected to harbour a BH, was repeatedly detected by SIGMA [13)]. It exhibited large brightness variations, correlated with spectral hardening.

Other persistent sources are though to be accreting BH binaries because of the similarity of their spectra to that of Cyg X-1, as the two hard sources 1E 1740.7-2942 and GRS 1758-258 [14)], extensively monitored since the beginning of the SIGMA/*GRANAT* mission. Both sources exhibit roughly analogous long term behaviors [15,16)], characterized by long periods (months) of bright state, followed by long periods of low state. Day to day variabilities are also apparent in both hard source light curves. Transient broad high energy features (beyond 200-300 keV) were detected in 1E 1740.7-2942 [17,18,19,20)], probably related to outbursts of pair formation.

The unprecedented statistics of the high resolution GC survey performed by SIGMA has made possible the determination of a more precise position of the hard source associated with 1E 1740.7-2942 [21)]. The improvement on the source position accuracy is such that the size of the error circle derived in the hard X-ray/soft γ-ray regime by a coded aperture instrument such as the SIGMA telescope, may now compare with that derived in the X-ray regime, where the source was first discovered. Radio observations with the VLA have revealed a compact variable radio source, the core of a double sided radio jet structure, close to the center of the improved SIGMA error circle [22)]. The identification of 1E 1740.7-2942 with the VLA compact source was strengthened when comparing its time variations at 6 cm wavelength with the hard source light curve [22,23)].

Soft X-ray transients. They are low mass X-ray binaries subject to episodic accretion, which become very bright in a few days, then decrease with a time scale around one month. In two members of this class, A 0620-00 [24)] and V404 Cygni [25)], the mass of the compact object was shown to be larger than 3 $M_\odot$, more than the NS limit. Their strong hard X-ray emission, although the spectra differ from one source to another, also put them on a par with other BH candidates such as Cyg X-1. SIGMA was conveniently on hand when a soft X-ray transient (GRS 1124-684) appeared in Musca in 1991 January, and could monitor the source from the earliest time of the flare [26,27)]. The optical spectroscopy allowing to measure the orbital elements of GRS 1124-684 had to wait for the optical emission of the nova to decrease below that of the companion ; its result put GRS 1124-684 in the list of BH candidate with a mass function of $3.1 \pm 0.5\ M_\odot$ [28)].

The average spectral shape was close to a power law of photon index -2.4. On 1991 January 20-21 SIGMA detected an emission line lasting more than 10 hours, centered around 480 keV, slightly below the energy of electron positron annihilation. It was the first such line observed in the spectrum of a soft X-ray transient. The fact that the source is clearly detected at the right position in the image derived in the energy interval where the line spectral feature is observed, substantially strengthens the overall confidence in the finding in such a case of a line detected in a spectral region where outstanding features are also detected in the background spectrum. A deeper analysis of the 1991 January 20-21 event reveals a complex picture of the source spectral evolution with the possible presence of two other high energy spectral features which could be interpreted as backscattered emission of the main line [29].

Another such a source (GRO J0422+32), which appeared in Perseus in August 1992, was observed in detail by SIGMA. It was at the time the brightest hard X-ray source in the sky (~ 3 Crab). It spectrum was comparable to that of Cyg X-1 [30] and its power spectrum revealed low frequency QPOs [31], most conspicuously around 0.3 Hz. By analogy with the other sources of this class, GRO J0422+32 is expected to be a new BH system. This is also the case of GRS 1716-249, the hard X-ray nova recently discovered by SIGMA in Ophiuchus [32]. Note also that SIGMA detected a sporadic hard emission from TrA X-1 [33], a soft X-ray transient whose largest outburst was observed on 1974 December 4 [34].

4.2. Neutron stars

NS systems. They form the bulk of X-ray binaries seen below 20 keV. Their spectra steepen earlier than those of BH systems, with cut off energies around 20 keV [35]. Indeed, none of the bright (~ 10^{38} erg s^{-1}, close to the Eddington limit) X-ray binaries has been detected by SIGMA, implying that their hard X-ray emission is less than 1% of the total. However, SIGMA has detected hard tails from two sub classes of X-ray binaries harbouring a NS. The X-ray bursters, which are relatively weak (~ 10^{37} erg s^{-1}) X-ray binaries, showed hard X-ray variabilities on time scales of a few days, as KS 1731-260 [36], MXB 1728-34 ≡ GX 354-0 [37] and A 1742-294 [38]. Similarly, outbursts of hard X-rays were also observed in the emission of binary X-ray pulsars, as OAO 1657-415 [39], GX 1+4 [40], GS 0834-429 [41] and Vela X-1 [42]. The high mass X-ray binary 4U 1700-37, in which a NS orbits the wind of its massive companion, is a case in point. This source also features hard X-ray outbursts [43], but the pulsar nature of the compact companion is not yet established.

Isolated fast pulsars. Although the time profile of the pulsed emission of PSR 0531+21 was measured soon after the launch of SIGMA/*GRANAT* [44], no other pulsed emission from fast isolated pulsars was detected by SIGMA via time analysis. On the other hand, the total emission (pulsed plus unpulsed component) from PSR 1509-58 has been detected after 192 hours of observations preformed in 1990-1993 [45]. By comparing the SIGMA flux to the pulsed flux measured by BATSE [46], one can estimate the pulse fraction in the 40-300 keV to be ~ 100%.

4.3. Black hole systems versus neutron star systems

On the basis of the results so far obtained by SIGMA, it has been proposed [14] that a direct relationship exists between the nature (NS or BH) of the compact object in a X-ray binary system and the overall spectral shape of its hard X-ray emission. Indeed, all sources known to be NS systems (X-ray bursters or binary X-ray pulsars) exhibit spectra which are clearly softer around 100 keV than the hard spectra of BH systems in their luminous states. As shown in Table 2 [47], the comparison of luminosities, taking distances into account, also clearly tells BH systems from NS systems. The 150-500 keV luminosity of NS systems was always less than a few 10^{35} erg s^{-1}, compared with positive detections at few 10^{36} erg s^{-1} for BH systems. The brightest NS system so far detected by SIGMA (4U 1700−377) maintained this luminosity for a few hours only [43], whereas the BH outbursts last a few weeks or more.

TABLE 2

Luminosity in the 150-500 keV band during luminous states in accreting binary systems [47]. An asterisk means that the distance is very uncertain.

Name	Nature	$L_{150\text{-}500\ keV}$ (10^{35} erg s^{-1})
GRO J0422+32	BH system ?	~ 115 (*)
GRS 1124−684	BH system	~ 50
GX 339−4	BH system ?	~ 30
1E 1740.7−2942	BH system ?	~ 40
GRS 1758−258	BH system ?	~ 20
Cyg X-1	BH system	~ 20
OAO 1657−415	Binary X-ray pulsar	≤ 1
4U 1700−37	NS system	~ 5
MXB 1728−34	X-ray burster	≤ 3
GX 1+4	Binary X-ray pulsar	≤ 2
KS 1731−260	X-ray burster	≤ 2 (*)
A 1742−294	X-ray burster	≤ 5

5. Extragalactic hard X-ray sources viewed by SIGMA

Before the launch of SIGMA/*GRANAT*, it has been often predicted that hard X-ray/soft γ-rays should provide a promising spectral band for studying AGNs, since most of the few data available at this time on AGNs detected beyond 100 keV indicated that a substantial fraction of the total luminosity in these sources is emitted in the hard X-ray/soft γ-ray band. The results derived from the SIGMA pointing devoted to the study of AGNs of various types should temper these predictions, even if the sensitivity of the telescope is such that the extrapolation of the X-ray AGN spectra indicates that only the brightest ones can be detected.

Marginally significant (3 σ) flux variations of the Seyfert 1 galaxy NGC 4151 were detected during the 1990-1992 SIGMA observations [48] in both 35-60 keV and 60-170 keV energy bands, but no significant variation in the hardness ratio was found. The steep source spectrum in hard X-rays, first detected by SIGMA in 1990 [49], and confirmed in later SIGMA observations [48], is much steeper than observed in lower energy X-rays and cannot be reconciled with previous detections in the hard X-ray/soft γ-ray regime. The 1990-1991 SIGMA observations of the quasar 3C 273 [50] indicate also a marginally significant (3 σ) 40-120 keV flux variation by a factor of two in a time scale as short as 41 days. The combined data of the first two pointing are well fitted with a power law of index ~ −1.5 up to about 500 keV, with no evidence for a break or steepening in the spectrum. The radio galaxy Cen A has been observed by SIGMA on three occasions in 1990-1991 [51]. A comparison between the observations indicates a flux increase by a factor of three over a one year time scale. Even more interesting is a similar decrease which was observed in just four days. Despite such intensity variations, the spectral shape of the emission remains unchanged and is well fitted with a power law of index ~ −2 up to about 100 keV.

Source confusion is not an exclusive prerogative of galactic regions but may also affect extragalactic fields as the Virgo cluster, which has been observed 10 times by SIGMA in 1990-1991. Among the well known AGNs of the Virgo cluster, only the Seyfert 2 galaxy NGC 4388 was detected, near the limit of visibility [52]. Contrary to the soft X-ray band, where prevails the giant elliptical galaxy M 87, the emission of the Virgo cluster at higher energies is dominated by NGC 4388. Similarly, the sky region around 3C 273 not only shows emission from the quasar [50], but also from a new hard source, GRS 1227+025, located 15′ away from 3C 273 [53], and tentatively identified with an uncatalogued *Einstein* variable X-ray source, whose optical counterpart is a faint QSO at $z = 0.57$ [54].

7. Conclusions

It should be first emphasized that the SIGMA concept, based on a static coded mask aperture operating in the hard X-ray/soft γ-ray regime, is fully certified, at least in the rather stable background environment experienced on the *GRANAT* highly eccentric orbit. The unique capabilities of coded aperture have been clearly demonstrated, as e.g. the aptitude to disentangle confuse regions, to enable firm identifications at other wavelengths and to perform reliable spectral measurements. In addition to the fact that source confusion is not an exclusive prerogative of galactic regions as the GC vicinity, but may also affect extragalactic targets, one of the most fundamental results which comes out from four years of successful in orbit operations with SIGMA is the high variability of the hard X-ray/soft γ-ray sky. With the exception of the sources powered by rotation, and with the exception of few persistent sources which are too weak to allow time variability determinations, all the sources so far detected by SIGMA are all time variable, and most of them are even strongly variable. The scales of variability range from minutes to years. This is also true for the spectral features so far detected in the emission of the soft γ-ray sources : none of them were observed during more than a day.

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