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Hard X–ray/Soft gamma–ray experiments and missions: overview and prospects

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Abstract Starting from 1960s, a great number of missions and experiments have been performed for the study of the high–energy sky. This review gives a wide vision of the most important space missions and balloon experiments that have operated in the 10–600 keV band, a crucial window for the study of the most energetic and violent phenomena in the Universe. Thus it is important to take the stock of the achievements to better establish what we have still to do with future missions in order to progress in this field, to establish which are the technologies required to solve the still open issues and to extend our knowledge of the Universe.

Keywords high-energy astrophysics · hard X-ray astronomy · space missions · balloon experiments

1 Introduction

It is recognized that hard X–ray/soft gamma–ray astronomy (10–600 keV) is a crucial window for the study of the most energetic and violent events in the Universe. An increasing number of missions devoted to observations in this band or including instruments specifically devoted to perform hard X–ray observations have been performed (e.g., *BeppoSAX*, *Rossi XTE*) or are still operational (e.g., *INTEGRAL*, *Swift*, *Fermi*).

Actually in the remote past this was only considered an ancillary energy band. The bands which were considered key for astrophysical observations were the 2–10 keV band, also dubbed classic energy band, and the soft X–ray band ($\leq$ 2 keV). The major efforts for X–ray observations were

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concentrated in these bands, e.g., *SAS-1* or *UHURU* satellite, *HEAO-2* or *Einstein* satellite, *EXOSAT*, *ROSAT*, *ASCA*, *Chandra*, *XMM-Newton* missions. In these large observatories, at most an extension to harder X-ray energies was foreseen by putting on board small hard X–ray instruments, e.g., *OSO-7*.

The first real attempt to survey the hard X–ray sky was performed with the NASA HEAO-1 observatory in which, in addition to very large instruments working in the classical X-ray astronomy band, a relatively sensitive instrument (HEAO-A4) was on board. In order to partially compensate the deficiency of sensitive hard X–ray instruments aboard satellite missions, many balloon experiments were performed. However, due to short flight durations, only studies of peculiar sources were possible.

With the ESA *INTEGRAL* observatory, and the NASA *Swift* satellite, unprecedented sky surveys in the band beyond 20 keV are being performed. As a consequence, hundreds of celestial sources have already been discovered, new classes of Galactic sources are being identified, an overview of the extragalactic sky is available, while evidence of extended matter-antimatter annihilation emission from our Galactic center and evidence of Galactic nucleo-synthesis processes have been also reported. In order to take full advantage of the extraordinary potential of soft gamma–ray astronomy, a new generation of telescopes is needed. The current instrumentation, mainly based on direct-viewing detectors, is penalized by its modest sensitivity, that improves at best as the square root of the detector surface. The only solution to the limitations of the current generation of gamma–ray instruments is the use of focusing optics.

To study the hard X-ray continuum spectra from celestial sources up to about 80 keV and their possible emission/absorption lines within this range, multilayer optics based on X-ray diffraction in reflection configuration, are now developed and, for the first time, launched aboard an American satellite (*NuSTAR*). However, if we want to study the continuum emission beyond 80 keV, a further effort is needed. Laue lenses, based on diffraction from crystals in a transmission configuration, are now under development and are possible candidates for extending the focusing energy band.

But, in order to establish how to face the future of the hard X–ray astronomy, it is important to take stock of the current status of the field, to know the instruments used, the observations performed with their limitations, and the results obtained. In this review paper, we outline the history of the main hard X–ray experiments flown aboard satellite missions and stratospheric balloons, their main features, their limitations and their main achievements. The list of all acronyms and abbreviations used throughout the text can be found in Table 3.

2 The birth of hard X–ray astronomy

Soon after the serendipitous discovery in 1962 by Giacconi et al. (1962) of an extrasolar X-ray source, Sco X-1, X-ray astronomy progressed rapidly. The first detection of a hard X–ray extrasolar source occurred in July 21, 1964 with a balloon-borne experiment of the Massachusetts Institute of Technology (MIT) (Clark 1965). The target source was the Crab Nebula, that was previously detected near 4 keV by Bowyer et al. (1964). The search for high–energy X–rays was an understandable curiosity. The X–ray detector was a scintillation counter made of a NaI(Tl) crystal of 97 cm^2 area and 1 mm thick. A slat collimator made of brass limited the FOV to 32 deg in one direction and 110 deg into perpendicular direction. The scintillation pulses were transmitted in 5 energy channels: 9–15 keV, 15–28 keV, 28–42 keV, 42–62 keV, and >62 keV. The balloon was launched from Palestine, Texas and achieved a float of 2.9 mbars. The Crab Nebula was observed

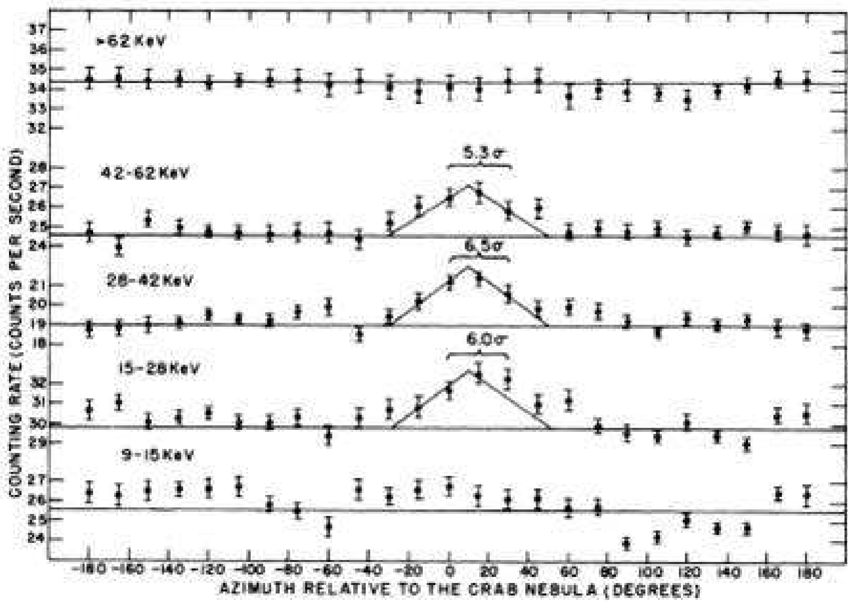

Fig. 1 The first discovery of an X–ray source (Crab Nebula) at hard X–ray energies. Reprinted from Clark (1965)

during the meridian transit (see Fig. 1). The average background level in the energy range 15 to 62 keV was $B = 1.6 \times 10^{-2}$ counts/(cm^2 s keV), with excess counts due to the source at the level of 5-7σ, depending on the energy channel. The spectral distribution was consistent with a power–law. So, thanks to a hard X–ray observation, for the first time it was possible to establish that the X–rays from the Crab Nebula were not due to blackbody emission, as expected from the surface of a neutron star, but were likely due to a non-thermal process.

One year later, on September 23, 1965, another balloon experiment was launched from Palestine, under the responsibility of Laurence E. Peterson of the University of California, San Diego (UCSD) (Peterson and Jacobson 1966) for observing the Crab Nebula. The energy band was 16 to 120 keV, the detector material was again NaI(Tl), the detector thickness was 5 mm and its area was only 9.4 cm^2, a factor 10 lower than that adopted by Clark (1965). However, the detector was actively shielded with a CsI scintillator and, as a consequence, the background level B was a factor of about 7 lower than that obtained by Clark (1965). The signal from the Crab was very clear and, for the first time, a 15 channel spectrum was obtained, determining for the first time the power–law dependence of the Crab Nebula photon spectrum ($F_\gamma \propto E^{-1.91\pm0.08}$).

With a similar balloon experiment, again under the responsibility of Laurence E. Peterson, Sco X-1 was observed for the first time at hard X–ray energies (Peterson et al. 1966). The launch was performed on June 18, 1965. It was possible to derive the spectrum of the source up to 50 keV, establishing that the data were well fit with an exponential law ($\propto \exp(-0.23E)$) up to 35 keV followed by a non-thermal component visible up to 50 keV.

In the same year, two balloon flights were performed from Hyderabad (India) with a payload which included a hard X–ray detector made of a NaI(Tl) scintillator of 7 inches diameter and 0.5 inch thickness, viewed by a 7 inch photomultiplier (PMT). The FOV of the telescope was about 20 deg, with its axis inclined with respect to the vertical by 22 deg. The FOV rotated around the vertical with a period of 11.2 min. Thanks to this rotation a region of the celestial sphere including the Cygnus region was scanned during the flight. For the first time Cyg X–1, discovered at low energies in the same year with a rocket experiment (Bowyer et al. 1965), was detected at hard X–ray energies from 20 to 58 keV (McCracken 1965).

Soon after the above balloon experiments, many others were successfully performed by X–ray astronomy groups spread over many countries (USA, France, Italy, The Netherlands, India, Japan). Most of them were devoted to observations of the Crab, Cygnus region, Sco X–1, Galactic Center region, and, for the first time, hard spectra and time variability were observed (Brini et al. 1967; Bleeker et al. 1967; Lewin et al. 1967; Chodil et al. 1968; Haymes et al. 1968; Peterson et al. 1968; Riegler et al. 1968; Overbeck and Tananbaum 1968; Rocchia et al. 1969; Glass 1969; Bingham and Clark 1969; Webber and Reinert 1970; Agrawal et al. 1971), (Deerenberg and Bleeker 1971; Agrawal et al. 1972; Matsuoka et al. 1972).

The interest for hard X–ray observations was also demonstated by the acceptance of a hard X–ray experiment aboard the 3rd Orbiting Solar Observatory (OSO 3), launched on March 8, 1967 and operational until November 10, 1969. The hard X-ray experiment was led by UCSD (Hudson et al. 1969a,b), and mounted on the spinning wheel of the satellite with a radial view. It consisted of a single thin NaI(Tl) scintillation crystal, 5 mm thick and 9.57 cm^2 area, viewed from a photomultiplier enclosed in a cup-shaped CsI(Tl) anti-coincidence shield 5 cm thick. The instrument operated from 7.7 to 210 keV with 6 channels. The FOV was 23° FWHM. It scanned the entire sky over the course of the mission.

Aboard OSO 6 there was a hard X–ray experiment (27–189 keV) (Brini et al. 1971a), devoted to studying both solar X–ray flares and the celestial sky. The detection of GRBs was obtained with this instrument (Pizzichini et al. 1975) soon after their discovery with the Vela satellites in 1973 (Klebesadel et al. 1973)

There was also a great interest for understanding the spectrum and thus the emission mechanism of the cosmic diffuse X–ray background (CXB), discovered at low energies by Giacconi et al. (1962). Many balloon and rocket experiments, but also observations with OSO 3, were performed during the 1960s to observe the CXB (e.g., Brini et al. 1970b; Schwartz et al. 1970). An exhaustive and critical review of the observations up to the early 1970s was performed by Horstman et al. (1975) (see Fig. 2).

Hard X–ray astronomy was born. Two key features were immediately clear: the determination of the emission mechanism of the celestial X–ray sources, and the detection of mysterious GRBs. Concerning the former, the spectrum derived in the classical X–ray band (2–10 keV), in spite of its importance, was in many cases insufficient to establish the emission mechanisms in play. Concerning GRBs, hard X–ray astronomy was crucial for their discovery.

3 Satellite missions and balloon experiments

Table 1 reports the main characteristics of the hard X–ray experiments aboard the main satellite missions, while Table 2 reports the main features of the balloon experiments devoted to hard X–ray astronomical observations. We discuss them and their most relevant scientific results in the following subsections, subdivided according to their decade of operation.

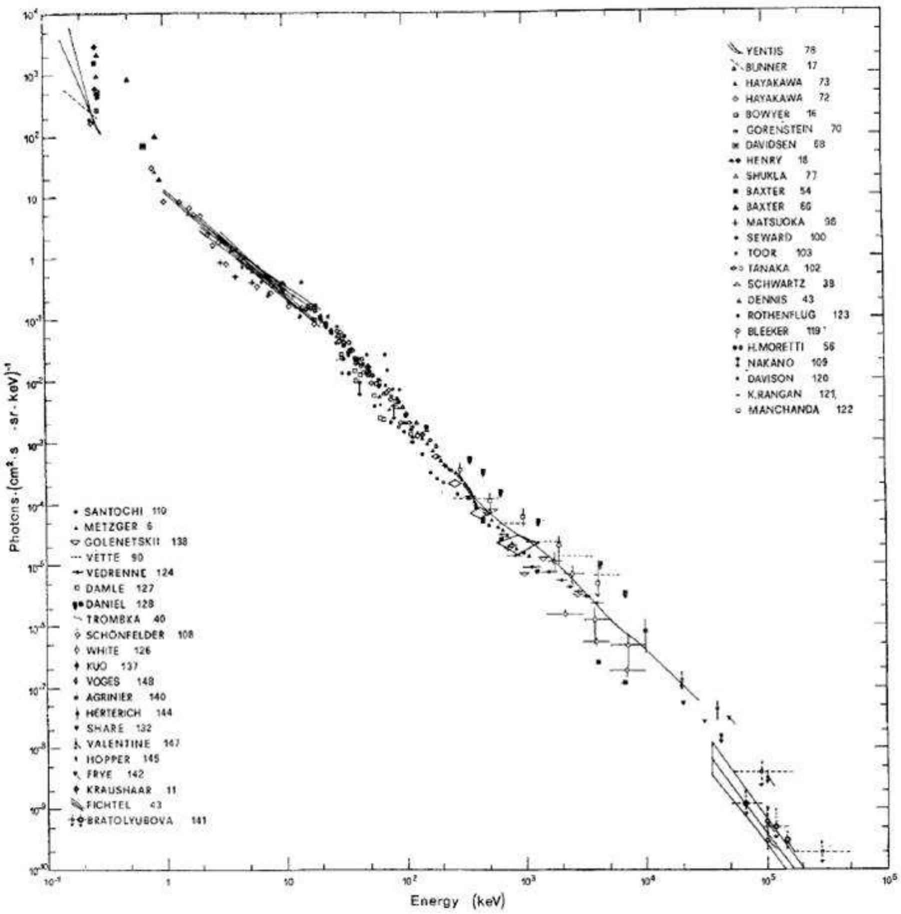

Fig. 2 The spectrum of the Cosmic X–ray Background as derived from the observations, mainly balloon experiments, performed up to the early 1970s. It could be described by two power–laws, one with index 1.590 ± 0.021 from 1 to 20 keV, and the other with index 2.040 ± 0.013 from 20 to 200 keV, with a break at 20 keV. Reprinted from Horstman et al. (1975).

Table 1: Main satellite missions

Mission	Launch date Site Termination date	Orbit Altitude (km) Inclination(°)	On board HE Instruments	Detector type	Thickness (g/cm^2)	Energy range (keV)	Energy resolution (%)	Useful or effective area (cm^2) (^{a})	FOV
OSO-3	8 March 1967 Cape Canaveral 10 November 1969	550 33	XRT	SD + C	1.835	7.7–210	45% @30 keV	9.57	23°
OSO-5	22 January 1969 Cape Canaveral July 1975	555 35	XRD	SD + C	2.86	14–254	nd	70	40°
OSO-6	9 August 1969 Cape Canaveral 31 December 1972	465–516 32.9	SXM	SD + C	4.66	25–190	28% @134 keV	5.1	17° × 23°
OSO-7	29 September 1971 Cape Canaveral 9 July 1974	321–572 33.1	HXT XCE	SD PC+C	3.67 0.061	7–500 1–60	33% @60 keV nd	64 186	6.5° 1–3°
Ariel 5	15 October 1974 San Marco (Kenya) Spring 1980	500–400 2.8	ST	SD	18.04	20–1200	30% @662keV	8	8°
OSO 8	21 June 1975	544–559	CXRS	PC+C	nd	2–60	nd	537	3–5°
	Cape Canaveral, USA 1 October 1978	32.9	HECX	SD+C	nd	20 keV–3 MeV	nd	27.5	5°
HEAO 1	1 August 1977	445–445	HED(A2)	PC+C	nd	3–60	nd	2700	various (see text)
	Cape Canaveral 9 January 1979	22.75	(A4) LED MED HED	PD+C PD+C PD+C	1.10 27.52 27.52	13–180 0.08–2 MeV 0.2–10 MeV	25% @60 keV 10% @1 MeV 10%@1 MeV	225 168 125	1.4°x20° 17° 10°
Venera 11-14	9-14 Sept.1978 Baikonur, URSS March 1983	variable NA	Konus	SD (6 units)	11.01	30–300	66% @200 keV	50/unit	4π
Hakucho	21 February 1979 USC, Japan 16 April 1985	521–533 29.9	HDX	SD+C	nd	10–100	nd	45	4.4°x10°
HEAO 3	20 September 1979 Cape Canaveral, USA 1 June 1980	486–505 43.6	HRGRS	SSD	~ 24	0.06–10 MeV	0.2% @1.46 MeV	75(@100 keV)	27°
Tenma	20 February 1983 USC, Japan	489–503 31.5	GSPC	GSPC+C GSPC+RMC	0.04	2–60	9.5% @6 keV	720	3.1–2.5° 3.8°
	11 November 1991		RBM/GBD	SD	nd	10–100	nd	14	1 sr
EXOSAT	26 May 1983 Vandenberg, USA 9 April 1986	347–191709 72.5	ME	PC+C	0.04	1–50	18% @22 keV	1800	45'
Ginga	5 February 1987 USC, Japan 1 November 1991	517–708 31.1	GBD	SD PC	3.67 0.02	14–400 2–30	15% @60 keV nd	60 63	no coll no coll
KVANT-MIR	31 March 1987 Baikonur, USSR 23 March 2001	354–374 51.6	HEXE GSPC Pulsar X–1	PD+C GSPC+C PD+C	1.17 nd nd	15–200 2–100 30–800	30% @60 keV 800 1.6° × 1.6° nd nd	 300 1256	 3° × 3° 3° × 3°
Granat	1 December 1989	2000–200000	SIGMA	PSD+CM	4.40	35 keV–1.3 MeV	8% @511 keV	794	11.4°x10.5°
	Tyuratam, USSR	51.6	ART–P	MWPC+CM	0.08	3–60	25% @6 keV	1160	3.6°x3.6°
	27 November 1998		ART–S	MWPC+RC	0.2	3–100	11% @ 60 keV	800(@100 keV)	2°x2°
			PHEBUS	SD	85.56	0.075–124 MeV	nd	280	no coll
			WATCH	SD+RMC	0.734	6–180	30% @60 keV	95	9 sr
			KONUS–B	SD	18.35	10 keV–8 MeV	nd	2200	non coll
CGRO	5 April 1991	362–457	OSSE	SD+C	36.7	0.05–10 MeV	8% @662 keV	2000(@511 keV)	3.8°x11.4°
	Cape Canaveral, USA	28.5	BATSE (LAD)	SD	4.66	30 keV–2 MeV	27% 88 keV	1.62 m^2	no coll
	4 June 2000		COMPTEL 31.20 (high Z)	CT	7.65 (low Z)	1-30 MeV	8.8% @1.27 MeV	10/50	1 sr

Table 1: Main satellite missions (continued)

Mission	Launch date Site Termination date	Orbit Altitude (km) Inclination(°)	On board HE Instruments	Detector type	Thickness (g/cm^2)	Energy range (keV)	Energy resolution	Useful or effective area (cm^2) (^{a})	FOV
Wind	1 November 1994 Cape Canaveral OPERATIONAL	L_1 Lagrangian point NA	Konus	SD (2 units)	27.96	10 keV –10 MeV	66% @200 keV	126/unit	4π
RXTE	30 December 1995 Cape Canaveral, USA 5 January 2012	409-409 28.5	PCA HEXTE	PC+C PD+C	0.02 1.1	2–60 17-240	18% @6 keV 15% 60 keV	6250(@6 keV) 1600	1° 1°
BeppoSAX	30 April 1996 Cape Canaveral, USA 30 April 2002	575–594 4	HPGSPC PDS	GSPC+C PD+RC	0.50 1.10	4–120 15–300	4% 60 keV 15% @60 keV	240 640	1°x1° 1.3°
HETE 2	9 October 1999 Kwajalein, Rep. Marshall Isl. March 2008	590–650 1.95	FREGATE	SD	3.67	6–400	12% @122 keV	120	3 sr
INTEGRAL	17 October 2002 Tyuratam, Kazakhstan	639–153000 51.7	SPI	SD+CM	37.24	20 keV–8 MeV	0.19% @1.3 MeV	250(through CM)	16° FC
	OPERATIONAL		ISGRI PICsIT	SSD+CM SD+CM	1.17 13.53	15 keV–1 MeV 175–10000	8% @60 keV 18% @511 keV	1300(through CM) 1400 (@500 keV)	9°x9° FC 9°x9° FC
Swift	20 November 2004 Cape Canaveral, USA OPERATIONAL	585–604 20.6	BAT	SSD+CM	1.17	15–150	2.2% @80 keV	2620 (through CM)	100°x60° HF
SUZAKU	10 July 2005 USC,Japan 2 September 2015	550–550 31	HXD/GSO HXD/PIN	PD+C SSD+C	3.35 0.46	40–600 10–70	24% @100 keV 3 keV	273(@150 keV) 160 (@20 keV)	4.5° × 4.5° 34'×34' (<100 keV)
AGILE	23 April 2007 Shriharikota, India OPERATIONAL	524–553 2.5	SuperAGILE	SSD+CM	0.095	18–60	8 keV	670 (through CM)	107°x68°
Fermi	11 June 2008 Cape Canaveral, USA OPERATIONAL	542–562 25.6	GBM/NaI GBM/BGO	SD SD	4.66 90.55	10 keV–1 MeV 150 keV–30 MeV	12% @511 keV 7.5% @2 MeV	1200 110	9.5 sr 4π sr
NuSTAR	13 June 2012 Kwajalen Atoll OPERATIONAL	610–650 6	XRT	PSD	0.37	3–78.4	1.3% @68 keV	847(@9 keV) 60(@78 keV)	10'(@10 keV) 6'(@68 keV)
ASTROSAT	28 Sept 2015 SDSC, Sriharikota OPERATIONAL	600 6	LAXPC CZTI	MWPC+C PSD+CM	0.37 1.24	3–80 10–150	13% @60 keV 2% @60 keV	6000 1000	1° × 1° 6° × 6°

^{a} With *useful area*, only used for non-focusing telescopes, we mean the detector geometrical area exposed to the source through a possible collimator or coded mask. With *effective area*, in the case of non-focusing telescopes we mean the geometrical area of the detector through a possible collimator or coded mask times the detection efficiency. Thus the effective area depends on photon energy. In the case of focusing telescopes, with effective area we mean the geometrical area of the mirrors projected on the focal plane times the reflection efficiency at a given energy E. When it is possible, we report the effective area in which also the detection efficiency is taken into account.

Table 2: The most significant hard X-ray balloon experiments

Group/ Experiment	Launch date Site Float altitude	Detector type	Thickness (g/cm^2)	Energy range (keV)	Energy resolution (%) (FWHM)	Useful or effective area (cm^2) (^{a})	FOV(FWHM)
Rice Un.	4 June 1967 Palestine (Texas) 3.35-3.65 mbar	SD+C	18.64	35-560	9.2% @511 keV	81	24°
	25 November 1970 Paraná (Argentina) 3.1-3.4 mbar	SD+C	18.64	23-930	9.2% @511 keV	75 (@661 keV)	24°
	1 Aprile 1974 Rio Cuarto (Argentina)	SD+C	18.35	0.02-12.27 MeV	12% @511 keV	182	13°
Tata Inst.	April 1968 Hyderabad (India) 5-7 g/cm^2	SD+C	1.47	22.5–154	nd	97	18.6°
	1985-1992 Hyderabad (India) 4.5 g/cm^2	MWPC	0.09	20-100	nd	2400	5°x5°
Bologna	23 June 1970 Gap Tallard (France) 5 g/cm^2	SD+C	4.66	20-200	20% @134 keV	136	13°
	1 July 1972 Gap Tallard (France) 6 g/cm^2	SD+C	4.66	30-200	30% @134 keV	280	13°
	29 July 1976 Trapani (Italy)	SD+C	4.66	20-300	poor	525	14°
NRL	17 October 1973 Palestine (Texas) 2.6 g/cm^2	PD+C PD+C	1.10(NaI) 1.35 (CsI)	20–160 20–160	35% @60 keV 35% @60 keV	70 70	20° 20°
	10 May 1976 Palestine (Texas) 2.3 g/cm^2	PD+C	1.83	20-250	24%@60 keV	765	10°
	24 November 1977 AS(Australia)	PD+C	1.83	20-250	24%@60 keV	765	5°
INPE	1973–1974 Sao Jos dos Campos (Brazil) 3.5-4 g/cm^2	SD	37.28	0.3-17 MeV	14% @511 keV	32	2π
	1978 Sao Jos dos Campos (Brazil) 3.5-4 g/cm^2	SD	2.33	0.1-2 MeV	14% @511 keV	32	2π
AIT/MPE	3 May 1976	SD+C	1.83	17-160	29% @60 keV	87	2°x10°
	Palestine (Texas) 2.8 g/cm^2	PD+C	1.10	15-135	22% @60 keV	108	2°x10°
	Sept–Oct 1977 Palestine (Texas) 3.1 g/cm^2	PD+C	1.10	10-200	22% @60 keV	766	3°
	1978 AS (Australia) 3.5 g/cm^2	PD+C	1.10	10-200	22% @60 keV	766	3°
ISAS	1977-1979 SBC (Japan) 5 mbar	SD+RMC	nd	30-200	nd	$\sim$ 500	146°
Uni. Tasmania	20 November 1978 AS (Australia) 3.5 g/cm^2	MWPC+C	0.11	20-100	nd	5200	7°x20°
MISO	1977,1978,1979,1980	CT	9 (NE311), 36.7 (NaI)	0.1–20 MeV	32% @1 MeV	560	3°x3°
	Palestine (Texas) 4 mbar	HXD	nd	20–280	nd	600	3°x3°

Table 2: The most significant hard X-ray balloon experiments (continued)

Group/ Experiment	Launch date Site Float altitude	Detector type	Thickness (g/cm^2)	Energy range (keV)	Energy resolution (%) (FWHM)	Useful or effective area (cm^2) (^{a})	FOV(FWHM)
Bell–Sandia	Sept 1977,April 1979 AS(Australia) 3.6 mbar	GeD	33.52	0.1–5 MeV	0.6% @511 keV	21	15°
MPI Compton-Tel	Oct.1977; May 1979 Palestine (Texas) 3.5	NE213+NaI	13.11(LS)+28.26(SD)	1–10 MeV	10% @2 MeV	24.4 (@1.5–2 MeV)	40°-50°
UCR Compton-Tel	10 Nov. 1981 AS (Australia) 4.5	LS(S1)+LS(S2)	10.87 (S1), 17.4 (S2)	0.3–30 MeV	20% @4 MeV	100 (@1 MeV, on axis)	60°
XG	1980, 1981 Palestine (Texas) 2.8 mbar	SD+C	3.67	20-200	23% @60 keV	1455	9.2°x9.2°
	1982 Milo Base (Sicily) 3.5 mbar	SD+PD+C	3.67+1.10	20-200	23% @60 keV	1455	9.2°x9.2°
POKER	1981, 1985 Milo Base (Italy) 2.4 mbar	MWPC+C	$\sim$ 0.2	15-200	13% @60 keV	2700x4	5°x5°
	May 1989 AS (Australia) 3.48-3.64 mbar	MWPC+C	0.21	15-280	13% @60 keV	2500x3	1.9°x1.9°
FIGARO II	July 1986, July 1990 Milo Base (Italy) 4 mbar November 1988 Queensland (Australia) 4–4.5 mbar	SD+C	18.35	170-6000	nd	3600	50°
MIFRASO	July 1986, 1987	SD+C(HED)	2.20	15-300	25% @60 keV	2700	2.6°
	Milo Base (Italy) 3.8-4 mbar	PC+C(LED)	$\sim$ 0.2	10–120	12% @60 keV	900	2.6°
EXITE	Oct. 1988, May 1989 Ft.Sumner(NM,USA), AS(Australia) 3–4 g/(cm^2)	PSD+C+CM	2.20	20-300	11% @122 keV	934	3.4°
GRIS	12 flights 1978–90 Ft.Sumner(NM,USA),AS(Australia) April, May 1992 AS(Australia)	GeD+C GeD+C	34.58 34.58	20-8000 20–8000	0.4% @500 keV 0.4% @511 keV	61.5 (@847 keV) 100 (@511 keV)	17°(@500keV) 18°(@500keV)
UAH-MSFC	3 flights 1987-1988 AS (Australia) 3 mbar	SD+C SD+C	4.66 4.66	18–960 18–960	$\sim$40% @80 keV $\sim$40% @80 keV	2027 2027	15.5° $\times$ 180° 30.75° $\times$ 180°
GRIP	May 1987, Nov. 1987, Apr. 1988, Apr.1989 AS (Australia) nd	PSD+CM	18.35	30–5000	16.6% @50 keV	500 (@200 keV)	18°
LXeGRIT	May 1999, Oct 2000 Ft. Sumner (New Mexico) -	CT	$\sim$ 21	200-25000	9% @1 MeV 2π	400	1 sr
HERO	24 May 2001 Ft. Sumner (New Mexico) 39 km	FO+PSD	0.27	20-45	5%	4 (@40 keV)	6’ (@40keV)
CLAIRE	14 June 2001 Gap-Tallard (France) 41 km	LL+GeD	21.28	167-173	1.4% @170 keV	64 (@170 keV)	1.5’
InFocμs	July 2001 Ft. Sumner(NM,USA) 36 km	FO+CZT	1.24	20-40	12.5% @32 keV	49 (@30 keV)	11’
HEFT	18 May 2005 Ft. Sumner(NM, USA) 39 km	FO+CZT	1.24	6-68	1.4% @70 keV	250 (@40 keV)	17’(@20keV)

Table 2: The most significant hard X-ray balloon experiments (continued)

Group/ Experiment	Launch date Site Float altitude	Detector type	Thickness (g/cm^2)	Energy range (keV)	Energy resolution (%) (FWHM)	Useful or effective area (cm^2) ([a])	FOV(FWHM)
protoEXIST1	9 October 2009 Ft.Sumner (NM,USA) 40 km	PSD+CM	3.1	30-600	10% @30 keV	256	9°x9°

[a] With *useful area*, only used for non-focusing telescopes, we mean the detector geometrical area exposed to the source through a possible collimator or coded mask. With *effective area*, in the case of non-focusing telescopes we mean the geometrical area of the detector through a possible collimator or coded mask times the detection efficiency. Thus the effective area depends on photon energy. In the case of focusing telescopes, with effective area we mean the geometric area of the mirrors projected on the focal plane times the reflection efficiency at a given energy E. When it is possible, we report the effective area in which also the detection efficiency is taken into account.

3.1 **Satellite missions and balloon experiments in the 1970s**

The seventies were the golden age of the balloon experiments, while most of the performed X–ray satellite missions were optimized for getting the best response and effective area in the classic X–ray energy band (2–10 keV), even if an extension to higher energies was preserved.

In the case of proportional counters (PC) on board satellites, the strategy generally adopted to extend the energy pass-band was that of having stacks of detector arrays one behind the other. The top array, filled with a low Z gas (e.g. Argon), functioned as an X–ray filter of the bottom array. The latter was generally filled with high Z gas (generally Xenon). In this way it was possible to extend the band even up to 60 keV.

To get a better efficiency at high energies than that of proportional counters, hard X–ray detectors based on scintillators of NaI(Tl), capable of efficiently detecting photons up several hundreds of keV, were developed and adopted. A further improvement in scintillator detectors was achieved with the introduction of phoswich detectors of NaI/CsI, that permitted high detection efficiency and a very low background (e.g., Frontera et al. 1997b). This type of instrument became the workhorse of both satellite missions and balloon-borne experiments until the present epoch. The balloon missions were devoted to specific studies of peculiar X–ray sources, while the satellite missions were designed also for the survey of the hard X-ray sky.

3.1.1 Satellite missions

Hard X-ray instrumentation was aboard almost all satellites dedicated to X–ray astronomy, such as *SAS-3*, *ARIEL-5* and *HEAO-1*, and also aboard satellites whose main goal was the study of the Sun, like the Orbiting Solar Observatories *OSO 3*, *OSO 5*, *OSO 6* (that we have discussed before), *OSO 7* and *OSO 8*. Most of the hard X–ray experiments in this decade had wide fields of view, allowing them to perform surveys of the sky. A particular case is that of the *Vela* satellites designed for nuclear test detection.

- **Vela series satellites**
  The Vela satellites represented a series of 12 military spacecraft with life time of the order of 1 year, launched between 17 October 1963 (Vela 1A and 1B) and 8 April 1970 (Vela 6A and 6B). Goal of the satellites was to monitor the explosion of nuclear bombs in the terrestrial atmosphere, which were vetoed by the Partial Test Ban Treaty issued on 10 October 1963.
  The satellites were spinning and had on board X–ray and gamma–ray detectors. The most sophisticated instrumentation was aboard *Vela 5* and *Vela 6*. It included a gamma-ray experiment (Klebesadel et al. 1973) which consisted of six CsI scintillation crystals, with a total volume of 60 cm^3, distributed so to achieve nearly isotropic sensitivity. The energy passband was 0.2-1 MeV in the case of Vela 5 and 0.3–1.5 MeV in the case of Vela 6. The scintillators were shielded for charged particles, thanks to a high-Z shield.
  On 2 July 1967, the Vela 3 and Vela 4 satellites detected a flash of gamma–ray emission unlike any known nuclear weapon signature. Other similar events were observed with other Vela satellites launched later and with better instruments. By analyzing the different arrival times of the bursts as detected by different satellites, the Los Alamos team led by Ray Klebesadel was able to determine rough estimates for the sky positions of sixteen bursts and to definitively rule out a terrestrial or solar origin (Klebesadel et al. 1973). In the time period 1969 to 1979 the Vela spacecraft (5 and 6) recorded 73 gamma-ray bursts. A preliminary catalog of events was reported by Strong et al. (1974).

- **OSO 5**
  OSO 5 was launched on January 22, 1969 with a Delta rocket from Cape Canaveral (US) and lasted until July 1975. For celestial X–ray observations, the instruments had to be located on the wheel section of the spacecraft, which, rotating, provided overall gyroscopic stability to the satellite. On the rotating wheel of *OSO 5* there was, among others, a CsI scintillation crystal (Frost et al. 1971). The energy range was 14–254 keV with 9 energy channels. It was primarily designed to measure, in addition to solar X-ray flares, the intensity, spectrum and spatial distribution of the diffuse cosmic background.
  The most striking result was indeed the spectrum of the diffuse background in the 14-200 keV energy range (Dennis et al. 1973).

- **OSO-7**
  The first relevant mission in the seventies with hard X–ray instrumentation was *OSO 7*. It was launched on September 29, 1971 by a Delta rocket and ended on July 9, 1974. The primary objectives were to perform solar physics experiments and to map the celestial sphere.
  The rotating wheel carried four X–ray instruments which looked radially outwards, and scanned across the Sun every 2 sec. Two of them were solar observing instruments, and the other two were cosmic X-ray instruments: the MIT X-ray Cosmic Experiment (**XCE**) and the UCSD Hard X-ray Telescope (**HXT**). We concentrate on these two instruments.
  The MIT **XCE** (Clark et al. 1973) (see also Table 1) was devoted to measure the positions, spectra and time variations of X-ray sources from 1 keV up to 60 keV. It consisted of two banks of gas proportional counters with cilindrical collimators that defined two circular FOVs, one with 1° FWHM and the other with 3° FWHM. Each bank had four counters. Starting from the front, the counters in each bank had Ne (1–6 keV), Ar (3–10 keV), Kr (15–40 keV) and Xe (25–60 keV) as the principal filling gas, stacked in such a way that each would act as a filter for those behind it (Markert et al. 1979). As the wheel rotated with a period of about 2 s, the FOVs swept out two circular scan bands in the sky. For each wheel revolution, the counts were accumulated in equal azimuthal bins, the content of which was sequentially telemetered. The angular resolution was about 14 deg. As the spin axis was precessed to maintain an angle near 90 deg from the Sun direction, the scan bands gradually swept over the sky. In this way all the sky could be surveyed.
  The UCSD Hard X-ray Telescope (**HXT**) (Peterson 1973; Cox 2000) was designed mainly to measure the spectrum and intensity of known and new X-ray sources in the 7-500 keV energy range. It consisted of a NaI(Tl) scintillation crystal (see Table 1) viewed by a Photomultiplier (PMT). The detector was surrounded by a 4 cm thick (Ulmer et al. 1972b) CsI(Na) anticoincidence shield, viewed by 6 PMTs, with 10 drilled holes to define its FOV (6.5°). Thanks to the wheel rotation, it provided a spatial resolution of 0.2°.
  Among the significant results, in addition to those on solar flares (e.g., Datlowe et al. 1974), there were a hard X–ray scanning of the sky with both the UCSD and MIT instruments (Peterson 1973; Markert et al. 1979), the first spectral studies extended to hard X–rays of strong Galactic (Ulmer et al. 1973a,b; Baity et al. 1973, 1974; Ulmer et al. 1974b,a; Ulmer 1975) and extra-galactic sources previously discovered with the *UHURU* satellite (e.g., Mushotzky et al. 1975, 1976), the discovery of the 8.7-day periodicity from Vela X-1 (Ulmer et al. 1972a) which led to its optical identification as a High Mass X–ray Binary (HMXB). Most of the results in the hard

X–ray band came from the UCSD instrument, given its higher efficiency than the proportional counter instrument of MIT (e.g., Clark et al. 1972).

– **OSO 8**
It was launched on June 21, 1975 by a Delta rocket and ended on October 1, 1978. OSO–8 consisted of a rotating wheel and a non-spinning upper section ("sail"). Four experiments were mounted in the rotating wheel to exclusively observe cosmic X-ray sources. The first three experiments had their fields-of-view either aligned to the spin axis of the spacecraft or at small angles to it. The fourth instrument observed cosmic X-ray sources during the satellite night. Only two of these experiments covered a significant part of the hard X–ray band: the Cosmic X-ray Spectroscopy (**CXRS**) experiment and the High-Energy Celestial X-rays (**HECX**) experiment.
The **CXRS** experiment (Serlemitsos et al. 1976) was designed to determine the spectra of point-like sources and the spectrum of the diffuse cosmic X-ray background in the 2–60 keV energy range. It consisted of two Xenon (A and C) and one Argon (B) proportional counters. Detectors A and C covered the 2–60 keV energy band. A was located behind a 5° collimator, with a Beryllium window and oriented antiparallel to the spin axis. Detector C was located behind a 5° FOV collimator with a Mylar window and oriented parallel to the spacecraft spin axis. The time resolution ranged from 160 ms down to 1.25 ms (Serlemitsos et al. 1976).
The **HECX** experiment (Dennis et al. 1977; Cox 2000) was designed to measure the energy spectra of celestial X-ray sources and the primary X–ray background in the 20 keV-3 MeV energy range. The detector consisted of 2 independent CsI(Na) crystals shielded by a large, actively collimated CsI(Na) shielding. The instrument axis was offset by 5 deg from the negative spin axis of the wheel. One of the two central crystals was completely shielded and served as a monitor of the internal detector background spectrum.
OSO–8 was devoted mainly to observations of Galactic X–ray binaries, with significant results at hard X–ray energies (the best up to 60 keV) on the brightest ones, e.g. Crab Nebula (Dolan et al. 1977), Vela X-1 (Becker et al. 1978), Cen X-3 (Dolan et al. 1984), Her X-1 (Maurer et al. 1979), AM Her (first time HECX and CXRS coincident spectrum over the range 2-250 keV) (Coe et al. 1979), Cyg X-1 (Dolan et al. 1979), 4U1700−37 (Dolan et al. 1980), Cyg X-3 (Dolan et al. 1982). Also high–energy spectral observations of the brightest AGNs, like NGC 4151 (Mushotzky et al. 1978) and Cen A (Beall et al. 1976), were performed.

– **Ariel V**
It was launched on October 15, 1974 from the San Marco platform (Kenya) and ended in the spring of 1980. The hard X-ray experiment was a High–energy Scintillation Telescope (**ST**).
ST was provided by the Imperial College, London University (Engel and Coe 1977; Coe et al. 1982) and was designed to extend the spectral information on selected X-ray sources in the energy region from 20 keV to 2 MeV. The detector was a disk of CsI(Na) scintillator actively collimated. The detector axis was inclined by a few degrees with respect to the satellite spin axis so that it rotated as the satellite spun. With this method the sources could be approximately located and the background removed.
Given the small useful area (8 cm^2, see Table 1), only strong sources could be detected. Positive results concerned the Galactic Center region (Coe et al. 1981a), Galactic source spectra and time variability, like Serpens X–1 (Coe et al. 1978); Cen X–3, GX301−2, and 3U1254−69 (Coe et al.

1976b), Circinus X–1 in outburst (Coe et al. 1976c); Cyg X–1 and the transient A0620−00 (Coe et al. 1976a); the discovery of the X–ray nova A0535+26 in hard X–rays (Coe et al. 1975); the detection of Am Her type degenerate dwarfs (Coe et al. 1978); the confirmation of the cyclotron line feature at 64 keV previously discovered by Trümper et al. (1977) from Her X–1 (see below) (Coe et al. 1977); spectral results on extragalactic sources, like NGC4151 (Coe et al. 1981b). A summary of the hard X–ray observations can be found in a paper by Coe et al. (1982), where for the majority of the observed sources only upper limits could be given.

– **SAS 3**

The Small Astronomical Satellite 3 (*SAS-3*), also known as *Explorer 53* or *SAS-C*, was launched on May 5, 1975 by a Scout rocket and ended in April 1979. It was the third of a series of small spacecraft intended to survey the X-ray sky locating the sources with an accuracy of 15 arcsec, and to study a selected set of sources over the energy range from 0.1 to 55 keV.

The payload included four instruments (Buff et al. 1977), one of which was a set of three slat collimator detectors (**SCDs**), made of proportional counters, looking out perpendicularly to the spacecraft Z-axis. One of the three **SCDs** had an extension up to 60 keV by positioning a Xenon counter behind the Argon counter. Its on–axis useful area was only 75 cm^2, three times lower than the Argon counters.

Few significant results of the many obtained with SAS 3 concerned the high–energy band, in particular observations of the strongest sources (e.g. Remillard and Canizares 1984; Doty et al. 1981).

– **HEAO 1**

The High–Energy Astronomy Observatories (**HEAO**) satellite series marked the epoch of large scientific payloads. The hard X–ray energies were successfully covered by the first satellite of the series, **HEAO 1**.

It was launched on August 12, 1977 by an Atlas–Centaur rocket and terminated its operations on January 9, 1979. It was designed to map and survey the celestial sphere for X– and gamma–ray sources in the 150 eV–10 MeV energy range, to establish the size and precise location of X–ray sources, to determine the contribution of discrete sources to the X–ray background, and to study peculiar X–ray sources and their time variations. The satellite could operate in scanning and pointing modes. In scanning mode it rotated clockwise about the Earth–Sun direction (z axis) with a period of 33 minutes. As the detector axes were directed perpendicularly to the z axis, each observatory rotation provided a scan of a great circle on the sky. When passing over the South Atlantic Anomaly (SAA), high–voltage supplies were turned off or reduced to prevent damage caused by saturation effects.

The experiments on board that covered also or only the hard X–ray passband were a Cosmic X–Ray experiment(**CX**) (also dubbed A–2) and a Low–Energy Gamma–Ray and Hard X–Ray Sky Survey experiment (**LEGR & HXSS**) (A–4).

The **A–2** experiment (Rothschild et al. 1979; Marshall et al. 1979) was designed primarily to measure the diffuse X–ray background in the 0.15–60 keV energy range. It consisted of 6 mechanically collimated, gas–filled, multilayer, multiwire proportional counters to cover 3 broad spectral bands. Three of them were high–energy detectors (**HED**) made of Xenon–filled (1 atm) proportional counters that covered the 3–60 keV energy range. Charged particles were rejected by a top veto layer of Propane–Neon. The 3 HED were collimated by the use of a dual FOV collimator which provided the same detector with two co–aligned sections having different FOV in the scan direction. Thus all collimator sections viewed 3° (FWHM) normal to the scan plane, while along the scan plane, one of the collimator sections viewed 3° FWHM and the other either 1.5° or 6° FWHM. This collimator configuration was designed to simultaneously measure both the diffuse X–ray flux and the detector internal background.

The **A–4** experiment (Jung 1989) was designed to measure point–like sources and the diffuse cosmic background in the 10 keV–10 MeV energy range. It consisted of 7 different collimated NaI(Tl)/CsI(Na) scintillators placed inside CsI(Na) wells: 2 Low Energy Detectors (**LED**), 4 Medium Energy Detectors (**MED**) and one High–Energy Detector (**HED**).

The **LEDs** were sensitive in the 13–180 keV energy range. The NaI(Tl) worked as a primary detector, while CsI(Na) as an active shield (phoswich configuration). Charged particles were rejected with a thin plastic scintillator covering the apertures.

The 4 **MED** (Bouchet et al. 2001; Cox 2000) phoswich detectors had an energy range of 80 keV–2 MeV with a small useful area (42 cm^2 each). Also in this case, the NaI(Tl) worked as a primary detector, and CsI(Na) as an active shield.

The **HED** phoswich detector (Cox 2000) had an energy range of 0.2–10 MeV. Similarly, the NaI(Tl) worked as primary detector and CsI(Na) as active shield.

Each of the detectors was equipped with a pulse–shape analyzer and a discriminator that recognized the true events and rejected the CsI(Na) events. The experiment also contained three particle monitors, which measured proton and electron fluxes in three energy ranges. There was a high–resolution timing system that allowed to measure GRBs.

One of the most important results of *HEAO-1* was the most complete and sensitive survey of the hard X–ray sky in the 13–180 keV energy band (Levine et al. 1984). Forty–four sources were detected in the 40–80 keV energy band, and 14 in the 80–180 keV band. Most of the sources are Galactic; seven are extragalactic (see Fig. 3).

Another key result was the most definite spectrum of the CXB in the 13–180 keV energy band (Gruber et al. 1999), previously observed mainly with balloon experiments (see Fig. 2). Results on the CXB in the 80–400 keV band were also reported using the A-4 MED experiment (Kinzer et al. 1997). Another key result was the CXB spectrum obtained with the A-2 experiment in the energy band from 3 to 50 keV. It was found consistent with free-free emission from an optically thin plasma of 40 ± 5 keV temperature (Marshall et al. 1980).

Many other results in the hard X–ray band, mainly obtained with the A-4 experiment, concerned spectra and time variability studies of single Galactic and extragalactic sources. Among the Galactic X-ray sources, significant results were obtained from X–ray pulsars like Her X–1 (Gruber et al. 1980; Gorecki et al. 1982), SMC X–1 (Gruber and Rothschild 1984), Cen X–3 (Howe et al. 1983), 4U1626−67 (Pravdo et al. 1979), 4U0115+63 (Wheaton et al. 1979), LMC X–4 (Lang et al. 1981); from bright X–ray transients (Cooke et al. 1984); from Low Mass X-ray Binaries (LMXBs), like Sco X–1 (Rothschild et al. 1980; Soong and Rothschild 1983). Also hard X–ray measurements of type I bursts were obtained, e.g., from MXB1728−34 (Hoffman et al. 1979).

A relevant result concerning the Galaxy Clusters was the discovery of a hard X–ray component from the Perseus cluster (Primini et al. 1981), and from the Centaurus and A1060 clusters (Mitchell and Mushotzky 1980).

Also obtained were the first spectra from the brightest AGNs, like those from Seyfert 1 galaxies up to 50 keV with the A–2 experiment (Mushotzky et al. 1980), and above 50 keV with A–4 (Baity et al. 1984; Dil et al. 1981)). Results from the radio galaxy Cen-A were obtained up to 2 MeV and from the quasar 3C273 up to 120 keV (Primini et al. 1979). A surprising result with

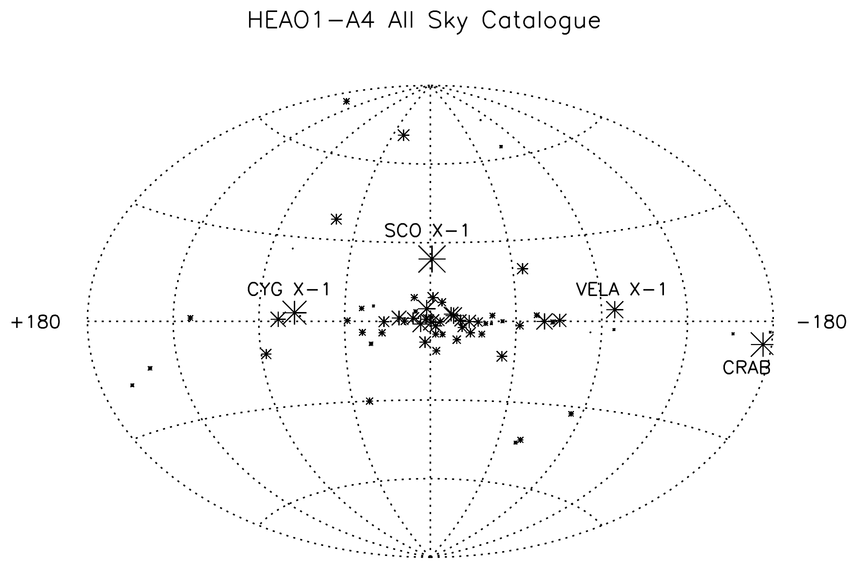

Fig. 3 The first view of the hard X–ray sky in Galacttic coordinates obtained with the HEAO–1 A4 experiment. The survey is complete, except in regions of source confusion, down to an intensity level of about 1/75 of the Crab Nebula in the 13–80 keV energy band. Figure derived from the catalog published by Levine et al. (1984).

the A-4 MED experiment was the discovery of a transient source near the Galactic Center in the 300–650 energy range, whose spectrum was consistent with a Gaussian (Briggs et al. 1994).

– **Venera 11-14**
The high interest of the scientific community to unveil the mystery on the origin and nature of GRBs discovered few years before (Klebesadel et al. 1973) affected also Russian astrophysicists who successfully proposed a hard X–ray/soft gamma–ray GRB experiment **Konus** aboard the Russian interplanetary missions *Venera 11* and *Venera 12* launched in Sept. 1978 (Mazets et al. 1979c). The experiment was developed by the Ioffe Physico–Technical Institute in St. Petersburg and consisted of six NaI(Tl) scintillators, which were completely open apart from a shield on the sides and bottom. The detectors were oriented along 6 different directions and covered all-sky. The different orientation of the detector axes allowed to get a localization of the GRB sources ≥ 4 deg, while, when the mutual large distance of the two missions was also taken into account, a localization in the arcmin range of the source direction was even possible through triangulation. In addition to the localization, it was possible to get temporal structure and photon spectrum of the events (Mazets et al. 1979c; Mazets and Golenetskii 1981).
A modified version of the **Konus** experiment flown aboard *Venera 11* and *Venera 12* was also flown aboard *Venera 13 and 14* launched in 1981 October 30 and November 4, respectively (Golenetskii et al. 1984). The main differences concerned the number of energy channels and a better time resolution. For example, the temporal accumulation of the photon spectra was 0.5 s instead of 4 s.
The Konus results were outstanding. Concerning GRBs, we wish to mention the important discovery, within single GRBs, of a time-resolved correlation between luminosity and peak en-

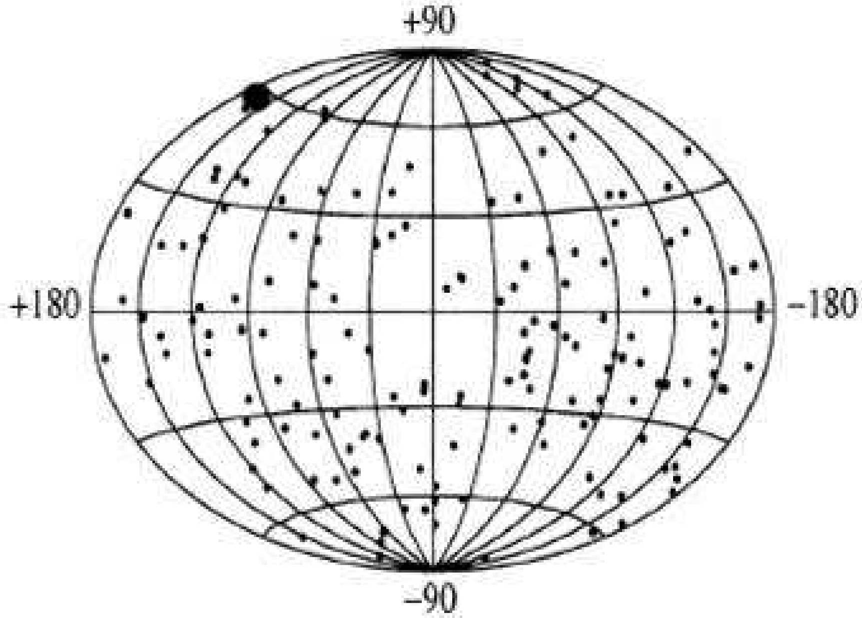

Fig. 4 Distribution of GRBs in the sky in Galactic coordinates as obtained with the Konus experiment aboard the Venera 11–14 missions. Reprinted from Mazets and Golenetskii (1988).

ergy (interpreted as bremsstrahlung temperature) of the $EF(E)$ spectrum (Golenetskii et al. 1983), and the earliest evidence of an isotropic distribution of the GRB positions in the sky (Mazets et al. 1981; Mazets and Golenetskii 1988) (see Fig. 4). Other key results concern the discovery on 5 March 1979 of the first pulsating burst, later called Soft Gamma Ray Repeater (SGR), from the supernova remnant N49 in the Large Magellanic Cloud (Mazets et al. 1979b): SGR 0526−66. Konus detected a total of 16 SGRs (Golenetskii et al. 1984), among which the famous SGR 1806−20 and SGR 1900+14 (Mazets et al. 1979a).

3.1.2 Balloon experiments

As discussed above, many X-ray astronomy groups performed balloon experiments soon after the first hard X–ray astronomy discoveries. The interest for balloon experiments continued in the 1970s, given the possibility of designing and performing them in a time much shorter than the satellite experiments and, thanks to the development of large balloon sizes, the possibility of launching large detection areas, much larger and sensitive than the satellite experiments. We discuss the most significant balloon experiments performed in the 1970s (see also Table 2).

- **Rice University group**
  With a hard X–ray instrumentation developed in the 1960s (Haymes et al. 1968), several balloon experiments were performed from USA and from Australia. Concisely the used detector consisted of a NaI(Tl) crystal viewed from a PMT. The FOV (24° FWHM) was obtained by means of a 10 inch diameter by a 12 inch long NaI(Tl) well scintillator that surrounded the central detector.

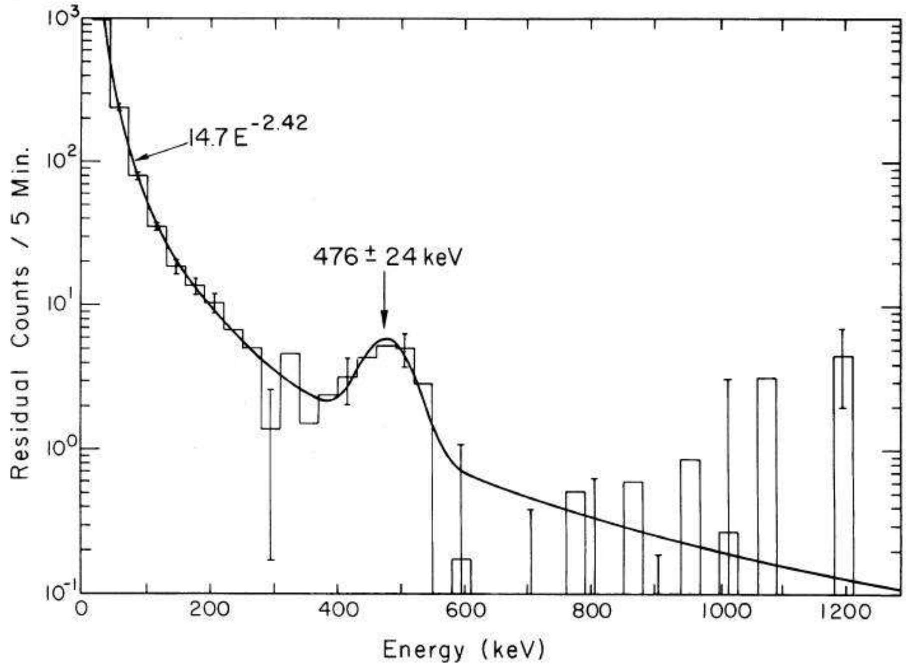

Fig. 5 The first discovery of a gamma–ray line from the Galactic Center Region, obtained with a balloon experiment. Reprinted from Johnson and Haymes (1973)

The spectra were collected in the energy band for 35 to 560 keV, with the events beyond 560 keV counted in a single integral channel. Significant spectral results were obtained from the Crab (Haymes et al. 1968), GX 3+1 (Haymes et al. 1969), the Cygnus region (X–1 plus X–3) (Haymes and Harnden 1970), Sco X–1 (Haymes et al. 1972), and the Galactic Center Region (Haymes et al. 1975).
Using the experiment above, but with an extended spectral band from 23 to 930 keV, two balloon flights were performed from Paraná (Argentina). The Galactic Center region was observed in both flights, and, combining the results, for the first time a significant (5.3σ) emission feature (see Fig. 5) at 476 ± 24 keV with a flux of $(1.8 \pm 0.5) \times 10^{-3}$ photons/(cm^2 s keV) was detected (Johnson et al. 1972; Johnson and Haymes 1973).
An improved balloon experiment was launched in 1974 from Rio Cuarto (Argentina). The experiment (Haymes et al. 1975) consisted of a NaI(Tl) crystal with a similar thickness and a larger cross section (see Table 2). The FOV was defined by a NaI(Tl) collimator. The energy range was 0.02-12.27 MeV. Among the results there was the observation of Cen A/NGC 5128 and GX 1+4 (Haymes et al. 1975; Koo and Haymes 1980).
The same experiment was flown in 1977 from Palestine (Texas). It was devoted to the observation of the Seyfert galaxy NGC 4151 and its long term time variability (Meegan and Haymes 1979).

– **Tata Institute group**

A balloon experiment was developed by the Tata institute of Fundamental Research in Bombay (India). The detector consisted of a thin NaI(Tl) crystal and a Beryllium entrance window. The FOV was obtained by means of a graded shield collimator of Lead, Tin and Copper. A plastic scintillator surrounding the detector acted as an anti-coincidence shield. The energy range was 22.5-154 keV.
With this experiment, several balloon flights were performed starting from April 1968 (Agrawal et al. 1971, 1972). The balloons were launched from Hyderabad (India) and lasted a few hours at the float altitude. They were dedicated to study the intensity, energy spectrum and time variations from various sources, such as Sco X-1, Cyg X-1, Crab (Agrawal et al. 1971, 1972). In an experiment performed on May 1, 1971, simultaneous hard-X and optical observations of Sco X–1 were performed (Matsuoka et al. 1972).

– **Bologna group**
Toward the end of the 1960s (Brini et al. 1970a), the detection system of the Bologna group was made up of two identical detectors of NaI(Tl) with a passband in the 20-200 keV energy range. A passive collimator together with semi-active anticoincidence (AC) shields around the central detector gave a triangular response with a FOV of 13° FWHM (Brini et al. 1971b).
The experiment (Frontera et al. 1972) was launched for the first time in 1970 aboard a stabilized platform to study the hard X–ray pulsating emission from NP 0532, the pulsar in the Crab Nebula (Brini et al. 1971a; Cavani et al. 1971). Another balloon experiment with the same instrumentation was performed in 1971, devoted to the observation of Cyg X–1 (Frontera et al. 1975).
With an improved detection system and same passband, a balloon experiment was launched in 1972. The detector consisted of a NaI(Tl) crystal with the same thickness and FOV, but with an increased area.
The goal was the long term variability study of Cyg X-1 and the observation of Cyg X-3 (Frontera et al. 1975). Combining the various observations of Cygnus X–1, an outstanding result was obtained (see Fig. 6): the first discovery of Quasi-Periodic Oscillations (QPOs) from the source with a frequency centroid of 5.75×10^{-2} Hz (Frontera and Fuligni 1975; van der Klis 1995). A confirmation of these QPOs was obtained with BATSE about 20 yrs later (Kouveliotou et al. 1993).
Another balloon experiment of the Bologna group was flown in 1976 from Trapani (Sicily) for a transatlantic flight. The flight terminated before arriving in the East coast of USA. The total useful duration was about 75 h (Frontera et al. 1981b). The experiment consisted of two independent collimated hard X-ray telescopes, 4 m apart, both pointing to the zenith. Each detector consisted of a large NaI(Tl) crystal. The nominal energy range was 20 to 300 keV. Due to telemetry limitations, the scientific data transmitted were the counts in 0.83 s in two energy channels (20-150 keV and 150-300 keV) and the 60 channel energy spectra integrated over 106 s. The detector background varied as a consequence of the change of both the geomagnetic latitude and the float altitude (Frontera et al. 1981b). Among the relevant results of this experiment there were the detection of pseudo gamma-ray bursts of long duration due to phosporescence in the detector produced by high–energy cosmic rays (Frontera et al. 1981a), the detection of a latitude effect in the X–ray counts (Frontera et al. 1981b), the observation of extragalactic (such as NGC 4151 and MCG 8-11-11) (Frontera et al. 1979a) and Galactic sources, like X Persei (Frontera et al. 1979b), and the discovery of a transient source (Fuligni et al. 1979).

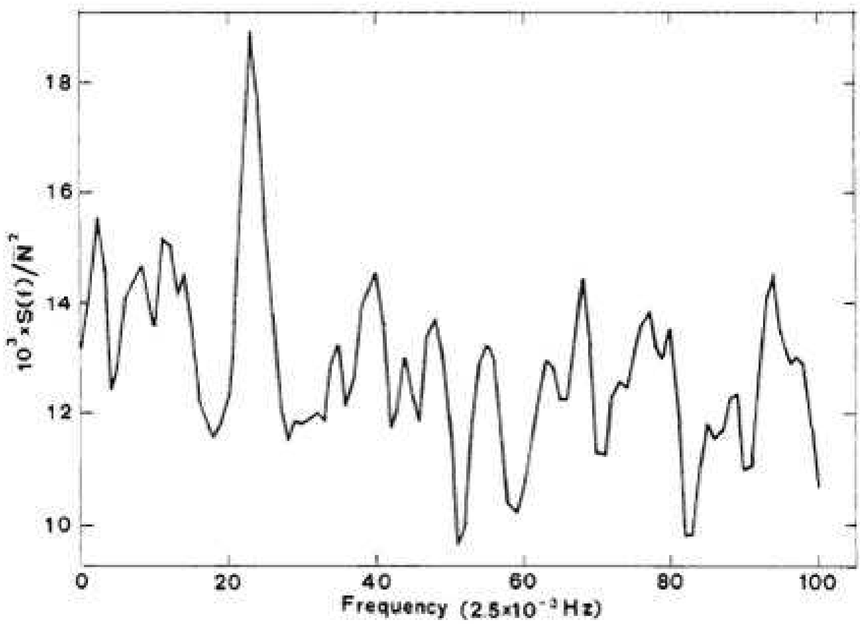

Fig. 6 Power Density Spectrum of Cygnus X–1, obtained from the results of three balloon experiments performed to study the source time variability. The first evidence of Quasi-Periodic Oscillations (QPO) was discovered. Reprinted from Frontera and Fuligni (1975).

– **NRL balloon experiments**
The first balloon experiment of the Naval Research Laboratory (NRL) performed in the 1970s was launched in 1973 from Palestine (Texas) (Kinzer et al. 1978). There were 2 phoswich X-ray detectors (A and B), that differed from each other only because of the CsI and NaI crystal roles interchanged. Both scintillators were viewed from a single Photomultiplier Tube (PMT). The energy passband was 20 to 160 keV. The two detectors were oriented vertically and were looking towards the north galactic pole. The balloon experiment was devoted to the measurement of the CXB spectrum above 20 keV (Kinzer et al. 1978).
After this experiment, an improved experiment with a larger detection area and 20-250 keV energy passband, was developed and, for the first time, launched in May 1976 from Palestine (Texas) (Johnson et al. 1978; Strickman et al. 1979). The FOV (10° FWHM) was defined by a graded collimator and could be oriented according to a programmed observation schedule. The experiment was devoted to the observation of several sources (Johnson et al. 1978), among which the Crab Nebula (Strickman et al. 1979) and Cyg X-1 (Johnson et al. 1978), from which significant fluctuations on time scales ranging from 10 s down to 0.1 s were observed.
The same experiment (Strickman et al. 1980) with a smaller FOV (5° FWHM) was also flown in 1977 from Alice Springs (Australia), with main objective the observation of GX 1+4 (Strickman et al. 1980).

– **INPE group, Brazil**
Also the National Institute for Space Research (INPE) in Sao José dos Campos (Brazil) developed a balloon experiment that was launched three times (Buivan et al. 1979) in 1973, 1974 and

1978 with flight durations of a few hours. The detector was a NaI(Tl) crystal 4 inches diameter by 4 inches thickness for 1973 and 1974 flights and 3 inches diameter times 1/4 inches thickness for the 1978 flight. The energy passsband was 0.9-17 MeV, 0.3-5 MeV and 0.1-2 MeV in 1973, 1974 and 1978, respectively. The flights of 1973 and 1978 were dedicated to the observation of the atmospheric gamma-ray component, while that of 1974 was dedicated to the observation of the Galactic Center region. The most significant result was the spectrum of the atmospheric gamma-ray emission (Buivan et al. 1979).

– **AIT/MPE group**
The first significant balloon experiment of the Astronomical Institute of the Tubingen University (AIT) in collaboration with the Max Planck Institute for Extraterrestrial Physics (MPE), was performed on May 3, 1976 from Palestine (Texas) (Kendziorra et al. 1977). Previously a balloon experiment was performed in 1975 (Pietsch et al. 1976). There were two independent collimated telescopes mounted in parallel: a NaI(Tl) scintillator detector (the same used in the 1975 flight) shielded by well type CsI crystals, and a NaI/CsI phoswich detector. Their passband was 17-160 keV and 15-135 keV, respectively. The FOV of both telescopes was $2^\circ \times 10^\circ$ FWHM. The balloon experiment was devoted to the observation of Her X–1, Cyg X–1, Cyg X–2 and Cyg X–3 (Trümper et al. 1978). The most important result was the first discovery of a strong line feature at 58 keV in the pulsed X-ray spectrum of Her X-1 (Trümper et al. 1977, 1978) (see Fig. 7).
An improved balloon experiment was launched two times in 1977, from Palestine (Texas (Staubert et al. 1978; Reppin et al. 1979; Staubert et al. 1980). The energy range was 10–200 keV. A passive graded shield (Pb, Sn and Cu) and a plastic anticoincidence scintillator were used to reduce the background. Also a radioactive source of ^{109}Cd was used to perform an in-flight calibration. During the first flight, the X-ray binary system AM Herculis was observed. By combining the flight results with those obtained with *OSO 8*, it was possible to derive an accurate spectrum of the source and find that it was consistent with a thermal bremsstrahlung spectrum (Staubert et al. 1978). During the second flight the time variability of Cyg X–2 was investigated (Reppin et al. 1979).
The same experiment was launched on November 22, 1978 from Alice Springs (Australia) reaching a float altitude of 3.5 g/cm^2. It was devoted to the observation of Vela X-1 (4U 0900-40) to study its 283 s pulsation and its hard X–ray spectrum (Staubert et al. 1980).

– **ISAS group, Japan**
With the goal of detecting GRBs, an ISAS (Institute of Space and Aeronautical Science) group (Yamagami et al. 1979) developed a balloon experiment which used a set of 3 NaI(Tl) scintillator detectors with 5 inches diameter, each located below a rotating cross-modulation collimator (RCMC), with a FOV of about 146° FWHM and a passband of 30-200 keV. The experiment, with the telescope axis directed toward the zenith, was launched three times in 1975 aboard a balloon for a total duration flight of 145 hrs.
Positive results were obtained with the detection and first accurate localization (within 0.2 deg) of a GRB event (Nishimura et al. 1978), two years after the publication of the GRB discovery. Other two long duration flights were performed in 1977 and 1979 (total duration of 138 hrs) with an improved experiment, made of an array of 4 detectors, each surmounted by a RCMC. Two GRBs events were detected and one of them accurately localized (Yamagami et al. 1979).

– **University of Tasmania group, Australia**

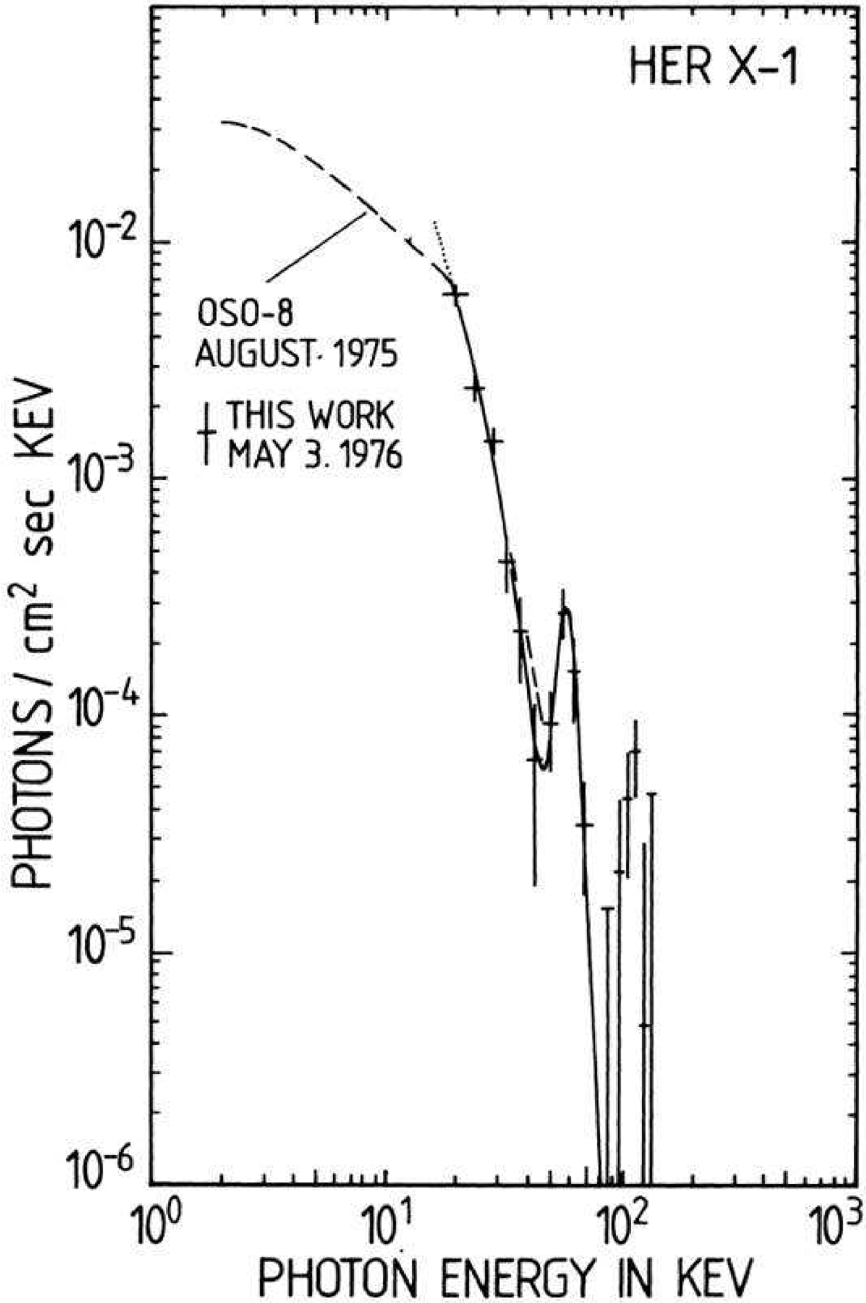

Fig. 7 X–ray spectrum of the X–ray pulsar Her X–1, with the first discovery of a cyclotron line. The result was obtained with a balloon experiment. Initially the line was interpreted as an emission line at 58 keV. Reprinted from Trümper et al. (1978).

A balloon group, operating at the University of Tasmania in Hobert, developed a balloon experiment that employed a multi-wire proportional counter (Greenhill et al. 1979a) filled with Xenon at a pressure of 716 mbar together with 304 mbar of Helium. It was sensitive to the 20-100 keV energy range. The detector was surrounded by veto counters and a graded shield of Sn and Cu. There was a collimator made of Nickel-plated pewter sheets, separated from the Xenon filled volume by means of an Aluminum window of 0.5 mm thick, but inside the hermetic chamber.
The balloon was launched in 1978 on November 20, 1978 from Alice Springs (Australia). Among its significant results there was the observation of known X-ray sources (Sco X-1, Cir X-1) and the observation of a transient event believed to be a gamma-ray burst (Greenhill et al. 1979b).

– **MISO collaboration**
The MIlan-SOuthampton (**MISO**) collaboration, established between the University of Southampton (UK) and the Institute of Cosmic Physics of the Italian CNR in Milan (Italy), developed a gamma-ray telescope operating in the 0.1-20 MeV energy range. The telescope consisted of two scintillators (a liquid scintillator NE 311, later replaced by a plastic scintillator, and a NaI(Tl)) that formed a Compton-coincidence detection system. The FOV (3° FWHM) was obtained by means of a semi-active shielding system. To extend the band to lower energies, a passively shielded hard X-ray detector (20-280 keV) was mounted parallel with the main telescope and the same FOV (Baker et al. 1979, 1981a; Perotti et al. 1986).
The experiment was successfully flown from Palestine (Texas) in May 1977, October 1978, September 1979 and May 1980. Positive results were obtained in the observation of the Seyfert I galaxies NGC 4151 (Perotti et al. 1979; Butler et al. 1981) and MCG 8−11−11 (Baker et al. 1981b), and in the observation of the sky region containing the bright high–energy gamma–ray source CG135+1 (Di Cocco et al. 1981).

– **MPI Compton Telescope experiment**
The Max Planck Institute for Extraterrestrial Physics (MPI) was the first institution that developed a Compton Telescope for soft gamma–ray astronomy (1–10 MeV) (Schönfelder and Lichti 1973). The telescope was based on the use of plastic scintillators for both the Compton scatterer and the absorber, both covered by an anticoincidence plastic scintillator. After this earliest development, the MPI moved to a Compton telescope based on an array of organic liquid scintillators as Compton scatterer and an array of thick NaI(Tl) inorganic crystals as absorber (Schönfelder et al. 1982). Also in this case, an anticoincidence shield of plastic scintillators was added.
Scientific results were obtained with both telescope configurations. With the earliest, the energy spectrum of the cosmic gamma–ray background (CGB) was measured (Schönfelder and Lichti 1974), and, thanks to the telescope half–opening angle of 20°, it was possible establish for the first time that at least 87% of the CGB was of extragalactic origin. With the second telescope configuration, two balloon flights had been performed: in 1977 and 1979. The first one was the most fruitful. It was possible to derive a sky map of the anticenter region of our Galaxy (Graser and Schönfelder 1981), the gamma–ray spectrum of Crab and its pulsar (Penningsfeld et al. 1979), and the spectrum of the diffuse (primary and terrestrial albedo) gamma–ray components (Schönfelder et al. 1980).

– **Groups committed to detect Gamma–ray lines**

Following theoretical studies by many authors (e.g., Meneguzzi and Reeves 1975; Lingenfelter and Ramaty 1976; Yoshimori 1979) on the possible production of Galactic gamma-ray lines and their detectability, a high interest was inspired in the search of these lines, in particular of the positron annihilation line at 0.511 MeV.
As discussed above, the first discovery of a spectral feature from the Galactic Center region at 476 ± 24 keV (see Fig. 5) was due to Johnson et al. (1972) and Johnson and Haymes (1973). It was interpreted by Leventhal (1973) as a positronium annihilation line. After this discovery, several balloon experiments were performed devoted to the search of gamma–ray lines (e.g., Buivan et al. 1979), but only a few significant results were found.
When the Crab Nebula was in the field of view of their gamma–ray telescope Yoshimori et al. (1979) reported the possible detection of a gamma–ray line at ~ 400 keV with a flux of $(7.4 \pm 5.4) \times 10^{-3}$ photons/(cm^2 s), never confirmed.
The most fruitful collaboration was that established by **Bell and Sandia Laboratories**. They developed a balloon telescope made of a Ge(Li) solid state detector 6.3 cm thick with a detection area of about 21 cm^2 and a FOV of 15°, working in the 0.1–5 MeV energy range (Leventhal et al. 1977, 1978). The FOV was obtained with a heavy anticoincidence shield of NaI(Tl) around the main detector. The gondola was alt-azimuth stabilized with a pointing accuracy of 1°.
Their most relevant result was the discovery, in a balloon flight performed on 1977 from Alice Spring, and confirmation with another flight performed in 1979, of a line feature at (510.7 ± 0.5) keV (Leventhal et al. 1978, 1980) from the Galactic Center direction (see Fig. 8). Its flux at the top of the atmosphere was $(1.22 \pm 0.22) \times 10^{-3}$ photons/(cm^2 s).

3.2 **Satellite missions and balloon experiments in the 1980s**

The 1980s saw the second generation of hard X–ray missions and balloon experiments. In the case of satellite missions, the highest interest was still devoted to the low energy band (< 20 keV), but an extension to higher energies (∼50 keV) was envisaged. In spite of that, in most of these cases no significant results were reported. This was also due to the fact that, in general, the analysis of the data collected in the hard X–ray band was much more problematic than at lower energies, where the signal-to-noise ratio was much higher. Only in few cases, *HEAO 3* and *Mir–Kvant*, significant results at high energies were obtained and reported. In the case of balloons, the 1980s decade was characterized by fewer but more sensitive experiments.

3.2.1 Satellite missions

– **Ariel VI**
Ariel VI was the follow up to Ariel V. It was launched on June 3, 1979 and operated until February 1982. The only instrument with an energy passband in the hard X–ray range was an X-ray Proportional Counter Spectrometer of the Leicester University. The instrument (Ricketts et al. 1982) consisted of an array of four multi-layered, Xenon-filled proportional counters with a total area of 300 cm^2, an energy passband from 1 to 50 keV, and an approximately circular FOV of 3° FWHM viewing along the satellite spin axis. It was designed for detailed measurement of time variability and spectra of both galactic and extragalactic sources, but the scientific output, at least at high–energies, was almost null due to electromagnetic interference from ground-based radar hampering the pointing operations.

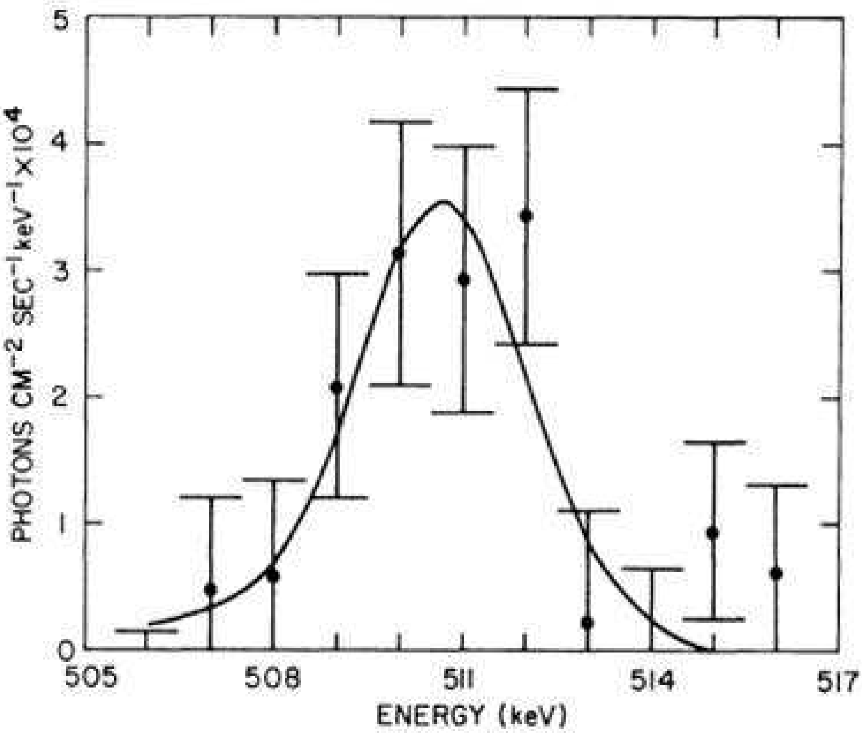

Fig. 8 First discovery of a positron annihilation line from the Galactic Center region with the Bell–Sandia balloon experiment performed on 1977 September 11-12. Reprinted from Leventhal et al. (1978).

– **Hakucho**
  The first X-ray astronomy Japanese satellite, *Hakucho*, was launched on February 21, 1979 and terminated on April 16, 1985. The payload included a Hard X-ray (**HDX**) experiment (Hayakawa 1981) consisting of a NaI(Tl) scintillation counter sensitive to the 10-100 keV energy range. In spite of the numerous outstanding results obtained at low energies on Galactic X–ray binaries (black hole candidates, bursters, pulsars) (e.g., Hayakawa 1981), supernova remnants (e.g., Inoue et al. 1979), etc, due to the very small useful area of HXD, no significant results were obtained at hard X–ray energies.

– **HEAO 3**
  The third HEAO mission was launched on September 20, 1979 by an Atlas-Centaur rocket and terminated on May 29, 1981. The experiments on board were a High Resolution Gamma–Ray Spectrometer (HRGRS) and two cosmic–ray experiments. The HRGRS (Mahoney et al. 1980) was developed to search for gamma-ray line emissions in the energy passband from 50 keV to 10 MeV. It consisted of four cooled, p-type, drifted-Germanium detectors shielded by a thick CsI anticoincidence shield. The energy resolution, initially 3 keV FWHM at 1.46 MeV, degraded with time because of radiation damage. It operated only for about one half year, until June 1, 1980 when the cryogen for the detectors exhausted.

Among the significant results there were the measurement of the Galactic Center 511 keV line, that gave an intensity of $(1.25 \pm 0.18) \times 10^{-3}$ photons/(cm^2 s) in the fall of 1979 and $(0.99 \pm 0.18) \times 10^{-3}$ photons/(cm^2 s) in the spring of 1980 (Mahoney et al. 1994), the discovery of the Al^{26} line emission (1809 keV) in the interstellar medium, the search for the 511 keV annihilation line from active galaxies (Marscher et al. 1984), the search for gamma–ray line emission from the the strongest known X–ray sources (e.g., Cyg X–1, Cyg X–3, SS 433), and a final negative response (Mahoney et al. 1984) to the issue of a possible line at 73 and 400 keV from the Crab pulsar reported by several authors (e.g., Ling et al. 1979; Strickman et al. 1982; Manchanda et al. 1982; Leventhal et al. 1977; Hameury et al. 1983).

– **TENMA**
The second Japanese X-ray astronomy satellite ASTRO-B, better known as **TENMA**, was launched on February 20, 1983, and terminated on November 22, 1985. It was designed to study spectra and temporal variations of X-ray sources, to make an all-sky survey for studying X-ray bursts and transients and to observe soft X-ray sources with a reflecting telescope. The observing efficiency was greatly reduced after a battery failure in July 1984. The experiments on board (Tanaka et al. 1984) included a Gas Scintillation Proportional Counter (2–60 keV; **GSPC**) and a Radiation Belt Monitor/Gamma-ray Burst Detector (10–100 keV; **RBM/GBD**).
The **GSPC** experiment with energy passband 2–60 keV (Tanaka et al. 1984) consisted of a set of 10 GSPCs, each made of a ceramic gas cell filled with 1 atm of Xenon and 0.2 atm of Helium, covered by a 100 μm thick Beryllium window and viewed by a suitable PMT. Four counters had a FOV of 3.1° FWHM, while another four had a FOV of 2.5°. The last two, with a FOV of 3.8° FOV, were surmounted by a bigrid rotating modulation collimator to improve the angular resolution. On–board calibration was performed using ^{109}Cd radioactive sources.
The **RBM/GBD** with energy passband 10 to 100 keV (Tanaka et al. 1984) consisted of 2 sets of NaI(Tl) scintillation counters. One of the counters was viewing in the direction of the spin axis and the other was scanning the sky with a fan-beam FOV. Detected GRBs were recorded with a time resolution of 1/8 s.
In spite of the many significant results on X–ray sources obtained at low energies, the extension to hard X–ray energies was limited, at most, to 20-30 keV for either Galactic (e.g., Nakamura et al. 1989; Leahy et al. 1989) or extragalactic sources (e.g., Miyoshi et al. 1986), with detailed spectral studies, inclusive of Iron lines, of the brightest Galactic ones (Inoue 1985). No results with the RBM/GBD were reported.

– **EXOSAT**
The European X-ray Observatory SATellite (EXOSAT) (Taylor et al. 1981) was launched on May 26, 1983. On April 9, 1986 a failure in the attitude control system caused the termination of the operations. EXOSAT reentered in the atmosphere on May 6, 1986. The experiment on board that covered a small part of the hard X-ray band was the Medium-Energy Cosmic X-ray (**ME**) experiment.
The ME detector (Turner et al. 1981) consisted of an array of 8 proportional counters sensitive in the 1-50 keV energy range. Each counter comprised 2 multi-wire proportional chambers, one in front of the FOV and the other on the back. The front chamber was filled with 2 bar Argon-Carbon dioxide, while the rear chamber was filled with Xenon-Carbon dioxide. The chambers were separated by means of a 1.5 mm Beryllium window. The front window was made of 62 μm Beryllium (32 μm for only one quadrant).

In spite of the numerous and outstanding results obtained with EXOSAT at low energies (< 20 keV), no significant results were reported at higher energies.

– **GINGA**
Also known as Astro-C, *Ginga* was a three-axis stabilized satellite, launched on February 5, 1987 and reentered the Earth atmosphere on November 1, 1991. It was designed to mainly study X–ray spectra and time variability of celestial, galactic and extragalactic sources. *Ginga* carried three scientific instruments (Makino 1987): a Large Area proportional Counter (**LAC**) (1.5–30 keV), an All-Sky X-ray Monitor (**ASM**) (1.5–30 keV), and a Gamma-ray Burst Detector (**GBD**) (1.5–400 keV). So, high energies were covered only by GBD.
GBD detector (Murakami et al. 1989) consisted of a proportional counter (**PC**) and a scintillation spectrometer (**SS**), both pointing to a direction parallel to the Z-axis of the satellite. The energy ranges were 2-30 keV and 14-400 keV for PC and SS, respectively. The **PC** was filled with Xenon and Carbon dioxide (10%) at 1.16 atm pressure, and an X–ray entrance window of 63.5 μm of Beryllium. The **SS** used a NaI(Tl) crystal coupled to a PMT via a light guide. The entrance window of SS was an Aluminum sheet of 0.2 mm thickness. The lateral cylindrical surface of the scintillator was covered by a graded passive shield. No collimator limited the FOV of the two detectors.
In addition to detect several GRBs (e.g., Murakami 1991), GBD seemed to show absorption features from some of these events, that immediately were interpreted as cyclotron absorption lines (Murakami 1989; Murakami et al. 1991). However these lines were never observed later in other GRBs.

– **Mir–Kvant**
The *Kvant* module, launched on 1987 March 31, was attached to the *Mir* space station. It operated until fall 1989 and was restarted in October 1990.
There were 4 instruments in the module. Apart from a coded mask imaging spectrometer (**TTM/COMIS**) working in the low energy band (2–30 keV), the other instruments (**HEXE**, **GSPC**, and **Pulsar X–1**), all coaligned, were working in the hard X–ray energy band.
HEXE (High–Energy X–ray Experiment) (Borkus et al. 1995) consisted of 4 individual phoswich detectors made of NaI(Tl) and CsI(Na) surmounted by a Tungsten collimator.
GSPC (or **Sirene 2**) was a high-pressure (3 atm) gas scintillation proportional counter covering the 2-100 keV energy range.
Pulsar X-1 consisted of 4 NaI/CsI phoswich detectors covering the 30-800 keV energy range.
Several observations of Galactic sources were performed, deriving the hard X–ray component of their emission. We mention here significant broad–band spectral results obtained on the Vulpecula X–ray nova (Sunyaev et al. 1988), the decay of the hard X–ray counterpart of SN1987A (Sunyaev et al. 1989), the Galactic Center region (Sunyaev et al. 1991b), bright black-hole candidates, X-ray pulsars and LMXBs (Sunyaev et al. 1991a), bright hard X–ray transients (Borkous et al. 1997; Kaniovsky et al. 1997).

3.2.2 Balloon experiments

We report here those experiments that gave the most significant results.

– **Bell–Sandia Laboratories experiments**

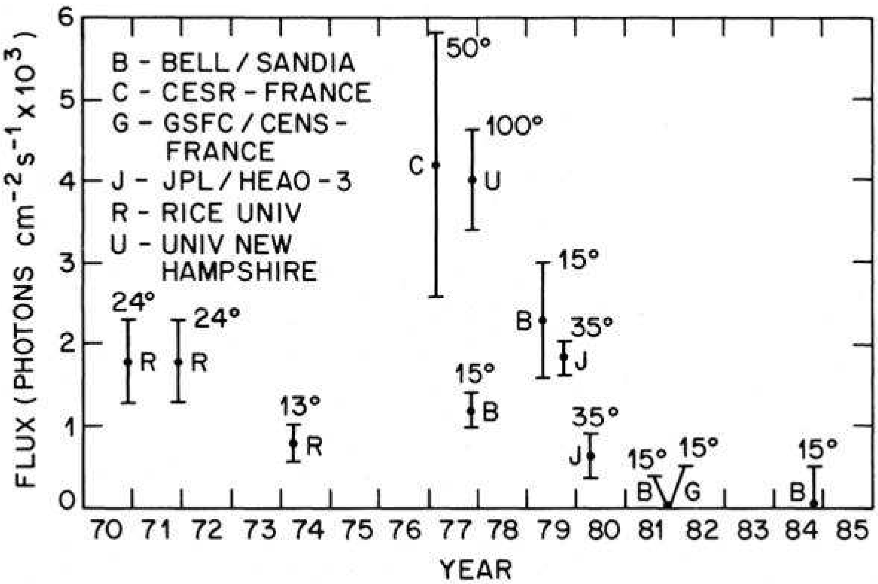

Fig. 9 The time behaviour of the 511 keV positron annihilation line from the Galactic Center region since its first discovery to 1984 November 20. The FOV of the instruments used is also reported, because there was the suspect that the line intensity could be correlated with the instrument FOV and thus that it could come from an additional source or that the source could be spatially extended (Dunphy et al. 1983). Reprinted from Leventhal et al. (1986).

The Bell–Sandia Collaboration (see above) continued in the 1980s with other balloon experiments mainly devoted to the monitoring of the Galactic Center (GC), from which a 511 keV positron annihilation line was previously detected (see above). Their balloon experiment was again flown from Alice Springs (Australia) on 1981 November 21 and 1984 November 20. The result was that the 511 keV line was no more detected, with 1σ upper limit of $\sim 4.4 \times 10^{-4}$ photons/(cm^2 s) (Leventhal et al. 1982, 1986). This result showed the variability of this line (see Fig. 9). However, measurements in the same epoch with the wide field ($\sim 130°$) **Gamma Ray Spectrometer** aboard the **Solar Maximum Mission** satellite, showed a strong 511 keV line ($2.3^{+0.5}_{-0.8} \times 10^{-3}$ photons/(cm^2 s)) with small variability (Share et al. 1990). This discrepancy and the positive detection in 1988 with the balloon experiment GRIS (see below) was interpreted by Lingenfelter and Ramaty (1989) as due to the presence of a point–like source near the Galactic Center and a diffuse line emission in the Galactic Center region.

– **UCR Compton Telescope experiment**
  A Compton telescope was also developed by the University of California in Riverside (UCR) (Herzo 1975), based on a double array of liquid scintillator tanks, the first array as Compton scatterer and the second one as absorber. An anticoincidence shield of plastic scintillators surrounded both arrays. The telescope exhibited an angular resolution of about 8° (HWHM). With this instrument, as a result of a flight performed in 1981 from Alice Springs (Australia), it was possible to report for the first time, in the 0.3–30 MeV energy band, on pulsations from the Vela pulsar PSR 0833−45 and its spectrum (Tümer et al. 1984).

– **XG experiment**
The **XG** experiment (from Italian X-Grande, i.e., X-Large) was a large balloon experiment of the Bologna group (Frontera et al. 1985c) with an operational energy band from 20 to 200 keV. It consisted of an array of 16 independent square NaI(Tl) crystals, each viewed by a PMT and separately collimated by a graded mechanical square collimator. The entire telescope was actively shielded by a plastic scintillator. Data were transmitted with a time resolution down to 1 ms.
The experiment was flown for two times from Palestine (Texas) in 1980 and 1981. In 1982 it was launched from the Milo base in Sicily. In the last flight four of the units were replaced with NaI/CsI phoswich units with different thickness values in order to select the best configuration for the high–energy instrument *PDS* for the BeppoSAX satellite (Frontera et al. 1985b).
In addition to spectral results obtained on Galactic (Cygnus X-1, Cygnus X–2, Her X–1, X-Persei, Crab Nebula) and extragalactic (NGC5548, Perseus Cluster) sources (Frontera et al. 1985a; Matt et al. 1990), the most significant and outstanding result was the high-statistics detection of the recurrent transient X-ray pulsar A0535+26 near the maximum of a large outburst. It was the first time in which single periodic pulses were visible, and, in addition to a study of the timing properties, a very detailed pulse-phase resolved spectral analysis (see Fig. 10) was possible to be performed (Frontera et al. 1985d; dal Fiume et al. 1988).

– **POKER**
POKER, a balloon experiment of the Frascati group, was flown in 1981 and in 1985 from the Milo balloon base in Sicily, and again in 1989 from Alice Springs, Australia.
The instrument (Bazzano et al. 1983) was a very large array of Multiwire Proportional Counters (MWPC) filled with a gas mixture of Xenon-Argon-Isobuthane. For the flights of summer 1981 and 1985, it consisted of 4 units of passively collimated MWPC, with an efficiency higher than 20% in the energy range 15-110 keV. For the flight of May 1989 the detector consisted of 3 MWPC modules instead of 4. To improve the background rejection, each MWPC and collimator module were surrounded with a plastic scintillator shield (Bazzano et al. 1990b).
Results were reported from all flights: for the 1981 flight, the detection of the recurrent transient X–ray pulsar A 0535+26 during one of its off–states (Polcaro et al. 1983), a hard X–ray detection of galaxy clusters (Bazzano et al. 1984) never confirmed; the detection of 3 AGNs (NGC 4151, MCG 8−11−11, Mkn 421) (Ubertini et al. 1984); for the 1985 flight, observation of Cyg X–1 and the Crab pulsar (Ubertini et al. 1991, 1994); while for the 1989 flight, observations of the radio galaxy Cen A (Ubertini et al. 1993), Sco X–1 (Ubertini et al. 1992), and the Galactic Center region were reported (Bazzano et al. 1992, 1993).

– **FIGARO II**
The French Italian GAmma Ray Observatory (FIGARO) was specifically designed to observe cosmic sources with a well-established time signature, like pulsars. The first version of FIGARO, launched the first time from Brazil in 1983, was destroyed following a balloon burst (Agnetta et al. 1985). Then it was reconstructed (FIGARO II) and successfully flown first from the Milo base (Trapani, Italy) in 1986, then from Charleville (Queensland, Australia) in 1988, and again from Milo base in 1990.
The principal detector of FIGARO II (Agnetta et al. 1985; Agrinier et al. 1990a) consisted of a square array of nine NaI(Tl) tiles. The energy passband was 0.2-6 MeV (Agnetta et al. 1989). The detector was actively shielded against the environmental background with a wall of 12

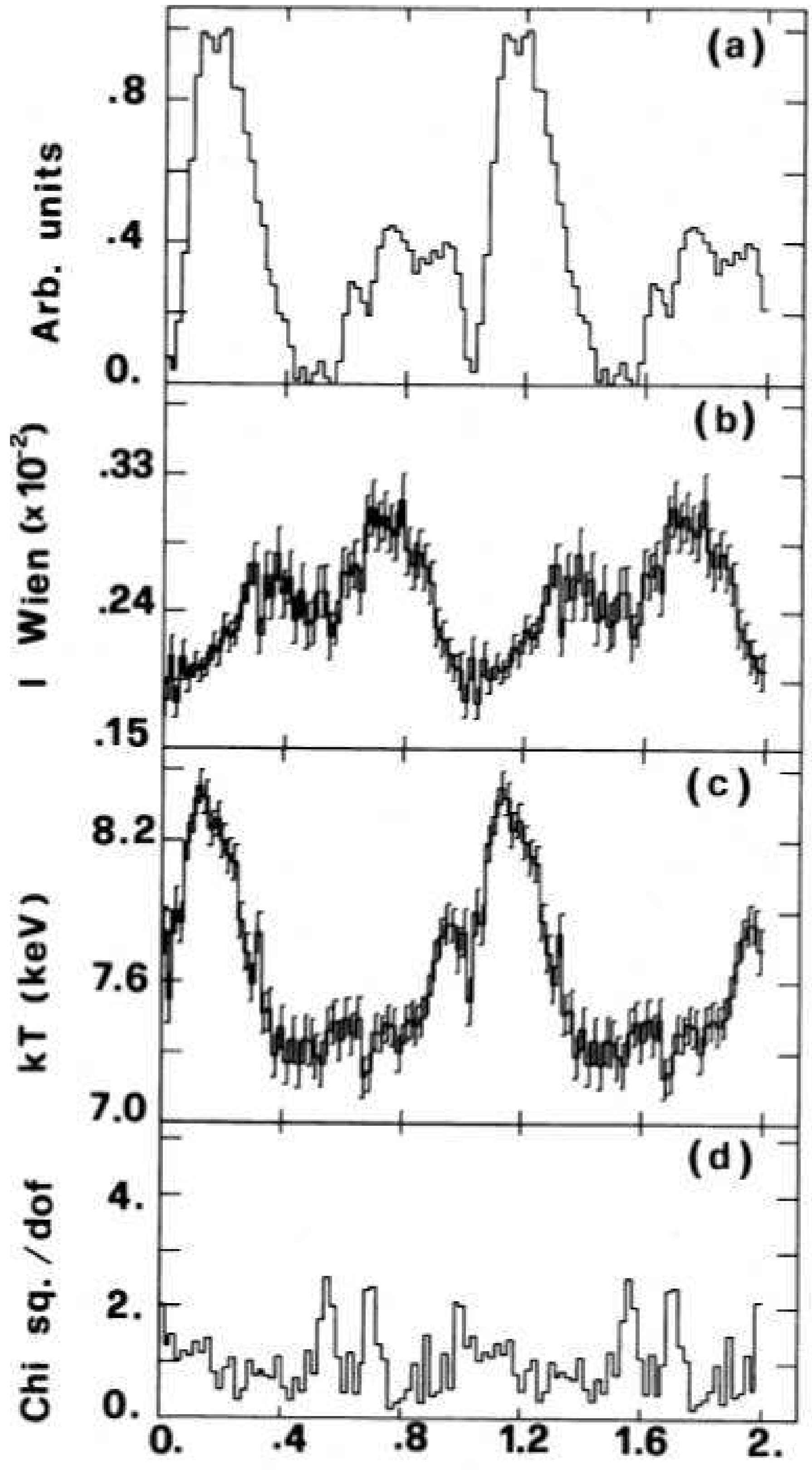

Fig. 10 Very detailed pulse–phase resolved spectroscopy in 27–100 keV of the X–ray recurrent transient pulsar A 0535+26 observed with the XG-experiment during a balloon flight on 5 October 1980 during a source outburst. The best fit spectrum was a Wien law. (a) Average pulse profile. (b)Intensity of the Wien law versus pulse phase. (c) Wien temperature versus pulse phase. (d) χ^2 per degree of freedom. It was the first time that a so detailed pulse-phase spectroscopy in hard X–rays was possible to be performed. Reprinted from dal Fiume et al. (1988).

NaI(Tl) modules along the four sides and a block of plastic scintillators from below. To reject charged particles from the entrance window there was a 5 mm thick plastic scintillator on the top of the experiment.
Significant results were obtained from all flights. The main goal of the first and third flight was the study of the Crab pulsar. Both the pulse profile and spectrum of the source in different energy bands were well determined (Agrinier et al. 1990b). The second flight was mainly devoted to the Vela pulsar PSR B0833−45, the brightest source in high–energy gamma–rays (>50 MeV). Very low upper limits to the source intensity in the instrument passband were reported (Sacco et al. 1990). A very intriguing result, but never confirmed, was the almost 3σ evidence of a 0.44 MeV line feature in the spectrum of the Crab pulsar (Massaro et al. 1991) observed during the third flight. During this flight, in addition to Crab, evidence of hard X–ray periodic emission (103.2 s) was reported from the binary pulsar A0535+26 during its "off" transient state (Cusumano et al. 1992)

– **MIFRASO**
The **MIFRASO** experiment (MIlano FRAscati SOuthampton collaboration) consisted of a High–Energy Detector (HED) and a Low Energy Detector (LED)(Baker et al. 1984). The HED was made of an array of eight identical scintillation counters of NaI(Tl) 6 mm thick, actively shielded on the bottom by an equal number of much thicker NaI(Tl) crystals (50 mm). The collimator was surrounded by a plastic scintillator as veto system.
The LED was made of two high-pressure Xenon gas proportional counters, sensitive in the 10-120 keV energy range.
MIFRASO was launched from Milo Base, Sicily (Italy) in 1986 and in 1987. The results concerned the hard X–ray detection of the Coma Cluster (Bazzano et al. 1990a), the quasar 3C273 (Dean et al. 1990), and the Seyfert galaxies NGC 4151 (Perotti et al. 1990a) and MCG 8−11−11 (Perotti et al. 1990b). Interesting was also the observation of A0535+26 far from the periastron passage (phase 0.25) (Coe et al. 1990) when outbursts were often observed (e.g., Frontera et al. 1985d).

– **EXITE**
The Energetic X-ray Imaging Experiment (**EXITE**), developed at the Harvard–Smithsonian Center for Astrophysics, was one of the first coded mask telescopes (Braga et al. 1990) with a 20–300 keV energy passband, flown aboard a stratospheric balloon. The central detector was a NaI(Tl) scintillator, optically coupled to an image intensifier tube. It was surrounded by a graded passive shield and by an active shielding of plastic scintillator. The space resolution was about 6 mm FWHM. The coded mask, with square cell side of 13 mm, was distant 2 m from the detector, yielding an angular resolution of 32 arcminutes FWHM at 100 keV and a location accuracy of about 25 arcmin. Two 1D crossed collimators, placed between the detector and the coded mask, defined a FOV of 3.4° FWHM. The coded mask had a Uniformly Redundant Array (URA) pattern.
EXITE was flown three times. The first flight was carried out in Alice Springs (Australia) in May 1988, with no scientific results due to a mechanical problem. The second balloon flight took place in Fort Sumner (New Mexico) in October 1988. The third flight took place in Australia, Alice Springs in May 1989, in the context of a NASA balloon campaign devoted to the supernova 1987A.

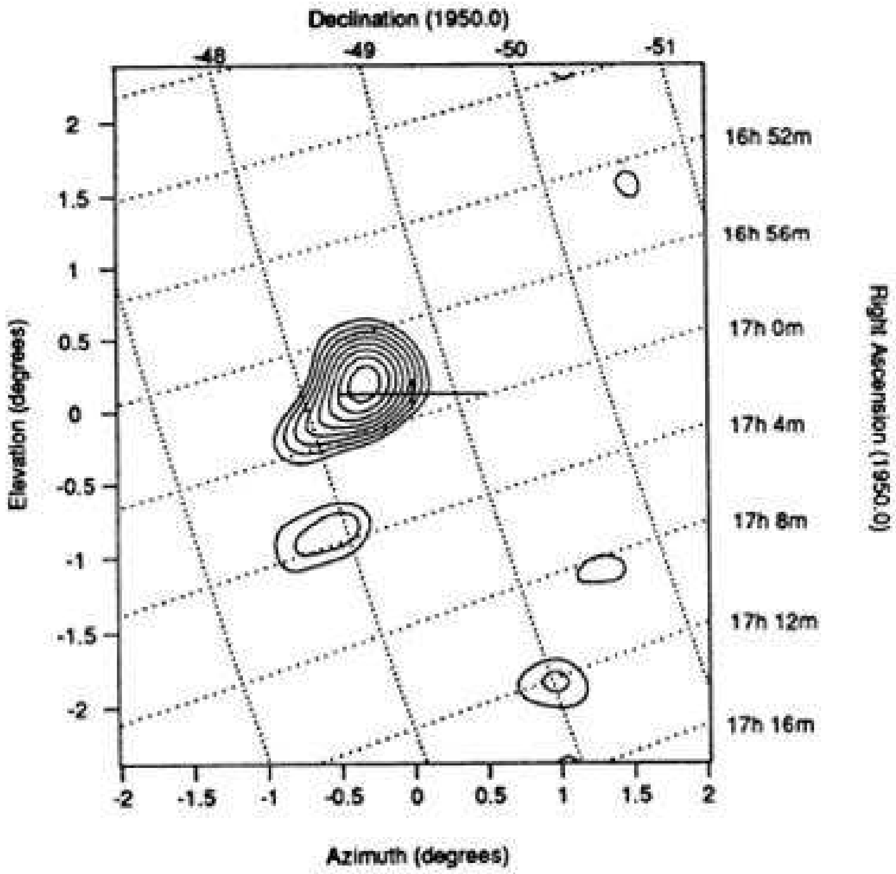

Fig. 11 One of the first hard X–ray images of a celestial source (GX 339−4) obtained with the coded mask aboard the EXITE balloon experiment. Reprinted from Covault et al. (1992).

A variety of both galactic and extragalactic objects were observed. Significant results include the hard X–ray detection of the *Einstein* source 1E1740.7-2942 with a possible second source, perhaps a transient source, about 40 arcmin West (EXS1737.9-2952) (Grindlay et al. 1993), and the first imaging observation of the black hole candidate GX 339−4 at hard X-ray energies (see Fig. 11) (Covault et al. 1992).

– **GRIS**

The Gamma-Ray Imaging Spectrometer (**GRIS**), developed at the NASA Goddard Space Flight Center, in collaboration with the Bell–Sandia Laboratories (Teegarden et al. 1985; Tueller et al. 1990), was a balloon-borne experiment using cooled Germanium detectors for high–resolution gamma–ray spectroscopy in the 20 keV–8 MeV energy range. The basic instrument consisted of an array of 7 coaxial high-purity Germanium detectors surrounded by a thick active NaI(Tl) shield/collimator. An active, uniformly redundant coded mask, was used to generate sky maps in its FOV, with a source positioning accuracy of 0.2°. Each detector was shielded by a 15 cm thick NaI active anti-coincidence shield.

GRIS had 9 successful flights (2 from Fort Sumner and 7 from Alice Springs) over 8 years, from 1978 to 1985. Later it was flown two times from Alice Springs (in 1988), where it was devoted to the observation of SN1987A. In 1990 it was again flown from Fort Sumner.
Among the results obtained from the GRIS campaigns there was the measurement of gamma-ray lines (rest energies of 846.8 and 1238.3 keV) from SN1987A (Tueller et al. 1990), and the positive detection, at a flux level of $(11.8 \pm 1.6) \times 10^{-4}$ photons/(cm^2 s), of the 511 keV positron annihilation line from the Galactic Center region (Gehrels et al. 1991; Cheng et al. 1997), after the negative results obtained in the early 1980s by Leventhal et al. (1982, 1986).

– **UAH–MSFC balloon experiment**
As a result of a collaboration between the University of Alabama in Huntsville (UAH) and the Marshall Space Flight Center (MSFC), a balloon experiment devoted to the observation of SN1987A was launched three times from Alice Springs (Australia): in October 1987, and in April and November 1988.
The experiment was based on two large area detection units of the same size and design as the LADs adopted for the BATSE experiment (see below) (Pendleton et al. 1995). A collimator based on passive slats of lead was adopted. The energy passband was 18 to 960 keV, with a different binning in different energy bands.
The results were very positive: in all flights SN1987A was detected and the spectrum determined up to 300 keV. The amount of ^{56}Co was constrained (Pendleton et al. 1995).

– **GRIP**
The Gamma–Ray Imaging Payload (**GRIP**) was an experiment developed at the CalTech Institute (Althouse et al. 1985). It consisted of a shielded detector system surmounted by a coded–aperture mask at 2.5 m distance. The detector was a position-sensitive NaI(Tl) scintillator viewed by 19 PMTs. A gain control was performed during the balloon flights. The background was minimized by using a side plastic shield and a bottom scintillator detector similar to the primary detector. The coded mask, made of Lead, with half of open pixels, had hexagonal cells in a uniformly redundant array and was rotating at 1 rpm for an unbiased background subtraction. The most important flights were those performed from Alice Springs (Australia) in 1987 (two times, May and November), 1988, and 1989. The 1987 flights were devoted to observe the supernova SN1987A. It was not detected in the first flight (Witteborn et al. 1987), but was clearly detected in the second flight (Cook et al. 1988), providing for the first time the gamma–ray image of a supernova. During the second and third flights gamma–ray imaging of the Galactic Center region was performed, deriving gamma–ray flux and spectrum of the brightest sources, among which, the *Einstein* source 1E 1740.7−2942 (Cook et al. 1991a,b; Heindl et al. 1993). Another important result was the non-detection of the 511 keV line. Assuming that the line emission was due to 1E 1740.7−2942, the 95% upper limits were 6.8×10^{-4} cm^{-2} s^{-1} for the 1988 flight and 3.7×10^{-4} cm^{-2} s^{-1} for the 1989 flight, confirming the time variability of this line (Heindl et al. 1993).

3.3 Satellite missions and balloon experiments in the 1990s

In the 1990s, a big effort on satellite missions was performed in order to extend the energy band up to hard X-ray rays. This effort was made possible by the use of new instruments, e.g, coded masks on board **GRANAT**. Here we discuss, in addition to GRANAT, **CGRO**, **RXTE** and **BeppoSAX**. We also devote attention to **COMPTEL** on board CGRO, although this experiment had a passband beyond hard X-rays.

Concerning balloon experiments, this decade was not characterized by significant experiments. Those launched were classical esperiments, mainly due to new groups entering into stage from emerging countries (Brazil, China, India) (e.g. Braga et al. 1995). Most of the efforts of the leading groups were devoted to the design of new imaging experiments, especially for long duration balloon flights, e.g. EXITE2 (Grindlay 1998), ALISE (Bazzano et al. 1991), AXEL (Sood et al. 1996), MARGIE (Cherry et al. 1995), LASE (D'Silva et al. 1998). An interesting review on the significant scientific results obtained with balloon experiments was reported by Teegarden (1994).

3.3.1 Satellite missions

– **GRANAT**
  Also known as **Astron 2**, **GRANAT** was the result of a collaboration between Russia and European countries. It was launched on December 1, 1989 with a Proton rocket and operated for almost 9 years until November 27, 1998.
  It was designed to study gamma-ray bursts and other transient X-ray sources, and also to image X-ray sources near the Galactic Center. The most relevant hard X–ray experiments on board were the X–ray/Gamma–ray Imaging Telescope **SIGMA** (35 keV–1.3 MeV), the X–ray telescopes **ART-P** (3–60 keV) and **ART-S** (3–100 keV), the gamma-ray burst monitor **PHEBUS** (0.075–124 MeV), the All-sky monitor **WATCH** (6–180 keV), and the Gamma-ray burst experiment **KONUS-B** (10 keV–8 MeV).
  SIGMA (Gilfanov et al. 1991; Burenin et al. 1999) was the result of a collaboration between CESR (Toulouse) and CEA (Saclay). It was designed to produce high-resolution images of the hard X–ray/soft gamma–ray sky. The telescope consisted of a position sensitive detector (PSD) surmounted by a coded aperture mask at 2.5 m distance with 15 arcminutes of angular resolution. The PSD consisted of a large NaI(Tl) disk (diameter of 57 cm) viewed by 61 hexagonal PMTs. The total useful area (see Table 1) was determined by the central rectangular zone of the PSD whose size matched the basic mask pattern. An in–flight calibrator was made of an ^{241}Am radioactive source. There was also an anticoincidence shield of CsI surrounding the camera, and a thin plastic scintillator located on the top of the PSD to veto the incoming charged particles. The CsI anticoincidence shield was used to detect GRBs (Pelaez et al. 1991).
  ART-P (Astrophysical Röngten Telescope) (Sunyaev et al. 1990), designed by IKI in Moscow, consisted of 4 coaxial, completely independent modules. Each of the modules included a position-sensitive MWPC surmounted by a coded mask to get an angular resolution of 5 arcmin and a positional accuracy of 1.5 arcmin. The best time resolution was 4 ms.
  ART-S (Astrophysical Röngten Telescope-Spectrometer) (Sunyaev et al. 1990) was also designed by IKI in Moscow. It consisted of 4 detectors based on spectroscopic MWPCs.
  The **PHEBUS experiment** (Talon et al. 1993; Vilmer 1994), designed by CESR (Toulouse, France), consisted of 6 independent BGO detectors surrounded by a plastic anticoincidence shield and oriented in such a way to obtain a complete open field of view. Phebus could operate in 2 modes: in the absence of a burst (waiting mode or Normal Mode) detected photons in the 0.1-1.6 MeV energy range with a 64 s time resolution were recorded. If the count-rate exceeded the background level by about 8σ the Burst Mode (BM) was activated, and a 31.25 ms time resolution was turned on.

The **WATCH** (Wide Angle Telescope for Cosmic Hard X-rays) experiment (Crosby et al. 1998), designed by the Danish Space Research Institute, was composed of 4 detection units mounted in a tetrahedral geometry. The detectors were based on rotation-modulation collimators with the second grid of the collimator replaced by 2 interleaved grids of NaI(Tl) and CsI(Na) detectors, viewed by a single PMT. The signals from the two types of scintillators could be separated electronically, due to the different decay characteristics of the scintillator materials. The modulation grid provided a 5.7° angular resolution. The instrument could localize bright sources within 0.5°. During a burst or a transient event, count rates were accumulated with a time resolution of 1 s into 36 energy channels.
The **KONUS-B experiment** (Golenetskii et al. 1991a), designed by the Ioffe Physico-Technical Institute in St. Petersburg to continue their research on gamma–ray bursts (Mazets and Golenetskij 1987), used 7 NaI(Tl) scintillation detectors distributed around the spacecraft. The lateral surface of the crystals was shielded with 5 mm thick Lead. When the counting rate in the 50–200 keV band was rising by 6σ over the background level, the energy spectra and time histories were acquired. The first 8 spectra were measured with 1/16 s time resolution while the remaining spectra had adaptive time resolutions depending on the count rate. The range of time resolution for the time histories was from 0.25 s to 8 s. The instrument operated only from 11 December 1989 to 20 February 1990. Over that period, 60 solar flares and 19 cosmic gamma-ray bursts were detected.
Many relevant results were obtained with the *Granat* observatory. Among them, we wish to mention the discovery of new sources, like the X–ray nova GRS 1915+105 with WATCH (Castro-Tirado et al. 1992), a very deep image of the Galactic Center region (e.g., Bouchet et al. 1991; Trudolyubov et al. 1999) with evidence of a short time (one day) transient bump around 500 keV from the Galactic micro-quasar 1E1740-294, the first discovery of a likely redshifted electron-positron annihilation line (480 keV) still from 1E1740-294 (broad) and from the X-ray Nova in Musca (narrow) (see Fig. 12) (Mandrou et al. 1994; Goldwurm et al. 1992; Gilfanov et al. 1991), the study of spectra and time variability of black hole candidates (e.g., Grebenev et al. 1997), the detection of many GRBs and their spectra (e.g., Golenetskii et al. 1991b). The reality of the 480 keV line from Nova Muscae has been contentious, but a new similar line at 511 keV recently observed from the microquasar V404 Cygni (see below) sheds a new light to the line from Nova Muscae.

– **CGRO**
The *Compton* Gamma Ray Observatory (**CGRO**) was launched on April 5, 1991 by the Space Shuttle Atlantis and reentered the Earth atmosphere on June 4, 2000. The hard X–ray/soft gamma–ray experiments on board were an Oriented Scintillation Spectrometer Experiment (**OSSE**), a Burst And Transient Source Experiment (**BATSE**), and a COMPton TELescope (**COMPTEL**).
OSSE (Johnson et al. 1993) consisted of 4 collimated NaI(Tl)/CsI(Na) phoswich scintillation detectors to provide gamma-ray line and continuum emission detection capability in the 0.05-10 MeV energy range. Each of these detectors could be individually pointed, allowing observations of a gamma-ray source to be alternated with observations of nearby background regions. The phoswich was enclosed in an annular shield of NaI(Tl) scintillation crystal in anticoincidence with the gamma-ray interactions in the phoswich. The anticoincidence shield had also the capability to measure the GRB rate. A plastic scintillation detector covered the detector aperture to get an anticoincidence shield to charged-particles. For most observations, two detectors were pointed at

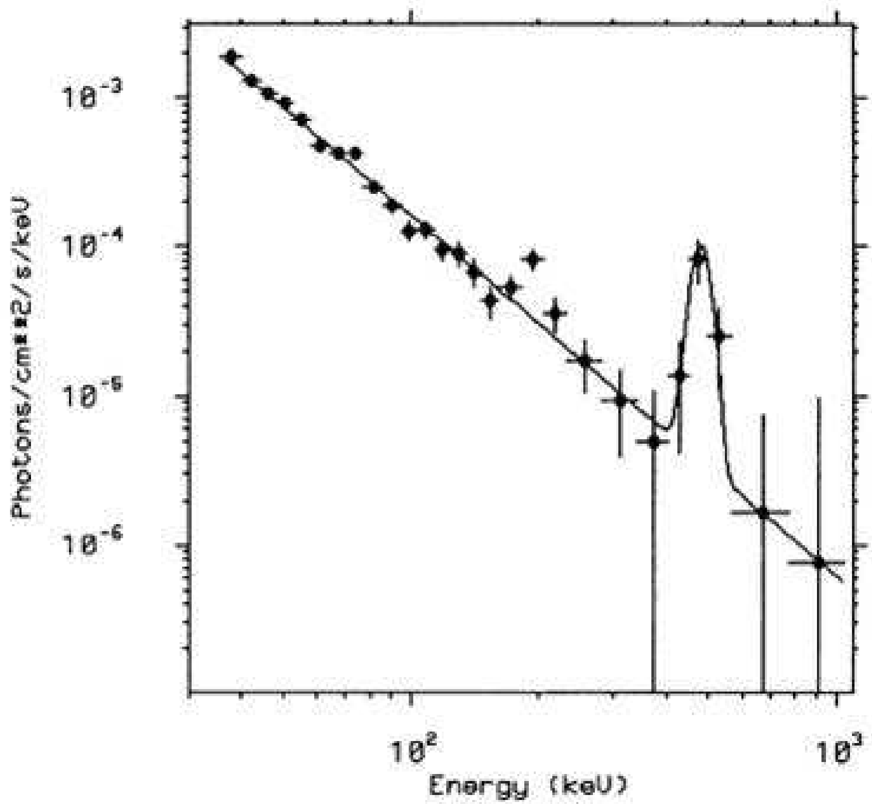

Fig. 12 First observation of a 480 keV emission line from a point-like source (Nova Muscae) with the SIGMA telescope, interpreted by the observers as a likely redshifted positron annihilation line. Reprinted from Goldwurm et al. (1992).

the source while the other two were offset for simultaneous background measurements. For time-variable phenomena, all four detectors could be pointed at the source for maximizing sensitivity.
BATSE (Fishman et al. 1992; Harmon et al. 2002), which was developed mainly to detect and locate gamma-ray bursts, consisted of 8, completely open, NaI(Tl) Large Area Detectors (LADs) at the corners of the spacecraft, each sensitive in the 30 keV-2 MeV energy range and with an area of 2025 cm^2. The GRB histories could be transmitted with different time resolutions down to μs time scales. For each LAD there was a smaller spectroscopy detector (SD) with a detection area of about 600 cm^2 (McNamara et al. 1995), optimized for energy resolution and broad energy coverage (10 keV–11 MeV). Some Earth occultation measurements were performed with the BATSE SDs.
COMPTEL (Schönfelder et al. 1993) explored the 0.75–30 MeV energy range with an angular resolution of 1–2 deg in its FOV. It consisted of two detector layers, an upper one of low-Z material (liquid scintillator NE 213A), and a lower one of high-Z material (NaI scintillator), separated from each other by a distance of 1.5 m. Each detector was entirely surrounded by a thin anticoincidence shield of plastic scintillator to reject charged particles. The effective area

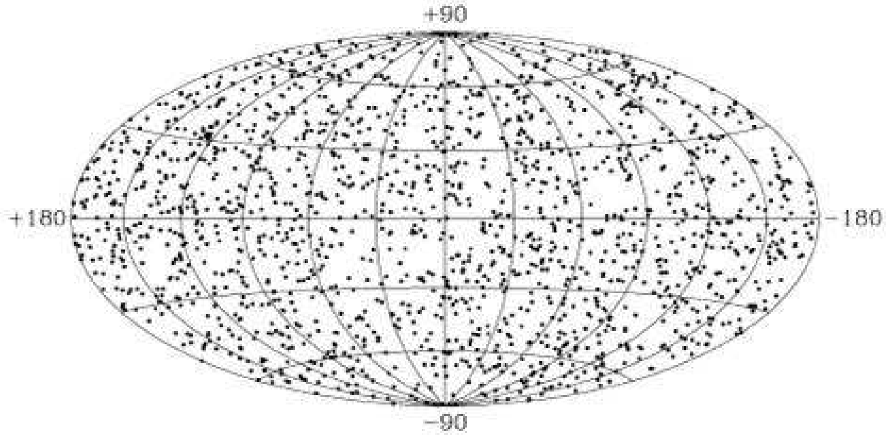

Fig. 13 Sky distribution in Galactic coordinates of 1637 GRBs detected with BATSE. Reprinted from Paciesas et al. (1999).

varied between 10 and 50 cm^2 depending on energy and event selection. The continuum and gamma-ray line source sensitivity are shown in Schönfelder et al. (1993).

Many significant results were obtained with *CGRO*. Among the many important results obtained with **BATSE**, we wish to mention the undeniable confirmation of the isotropic distribution of the GRB events (see Fig. 13) (e.g., Paciesas et al. 1999), the first hint of which, as we have seen, was earlier reported by Mazets and Golenetskii (1988). A GRB isotropic distribution was crucial to exclude their origin as being in the disk of our Galaxy, but did not excluded the possibility that they could be either local or have origin in an extended halo of our Galaxy with a typical source distance of about 100 kpc (e.g., Hartmann et al. 1994). A significant discovery of BATSE was that of a unique object GRO J1744−28 called "the Bursting Pulsar" (Kouveliotou et al. 1996). Broad band spectrum and phase analysis of the source were later measured with OSSE (Strickman et al. 1996).

Among the outstanding results obtained with **COMPTEL**, we mention the mapping of the Milky Way using the ^{26}Al Gamma-ray line (Diehl et al. 1994), the detection of the first soft gamma–ray pulsar PSR B1509−58 (Kuiper et al. 1999), and the discovery of only Blazars as AGNs emitters at MeV energies (no Seyfert galaxies), opening the field of gamma–ray astronomy (Collmar et al. 1999).

With **OSSE** numerous results were obtained. We wish to mention the measurement of the 511 keV positron annihilation line from Galactic Center region at a flux level of $(2.5 \pm 0.3) \times 10^{-4}$ photons/(cm^2 s) (Purcell et al. 1993) and its mapping (Purcell et al. 1997), and the measurement of the broad band spectrum and time variability from Galactic and extragalactic sources (e.g. Grove 1996). Most classes of X–ray sources, compatible with the instrument sensitivity, were investigated, from X–ray pulsars (e.g., A0535+26 from which an absorption feature at 110 keV was discovered (Grove et al. 1995)), to supernova remnants (e.g., Vela (de Jager et al. 1996)), Galactic center sources (e.g., 1E 1740.7−2942 (Jung et al. 1995)), BH candidates (e.g., Grabelsky et al. 1995; Phlips et al. 1996), radio galaxies (Kinzer et al. 1995), Seyfert galaxies (e.g., Maisack et al. 1993; Fabian et al. 1993; Johnson et al. 1994; Zdziarski et al. 1995; Bassani et al. 1995; Johnson et al. 1997; Zdziarski et al. 2000), starburst galaxies (Bhattacharya et al.

1994), blazars (e.g., McNaron-Brown et al. 1995).

- **Wind interplanetary mission**
  Thanks to an agreement between USA and the Russian Federation, an upgraded version of the **Konus** experiment aboard *Venera* 11-14 missions was launched aboard the American *Wind* spacecraft, launched in 1994, and still operational. The new Konus consists of two detection units made of NaI(Tl) scintillators completely open apart from a shield on the sides and on the bottom of the detector, similarly to the previous Konus configuration. The two units were oriented along the spin axis of the spacecraft, one looking toward the top and the other toward the bottom, covering in this way the full sky. Currently the energy range is 20 keV to 15 MeV (Aptekar et al. 2012).
  Several thousands of GRBs have been detected so far, providing for each of them a broad band spectrum. Thanks to its very high distance from the Earth, Konus–Wind provides an almost unbiased rate of GRBs and of other transient events, like SGRs (Aptekar et al. 2012). The event localization on the sky can only be obtained by combining the arrival time of the events at Konus–Wind and at other gamma-ray satellites (Interplanetary Network, IPN). Most of the results obtained with Konus–Wind can be found in GCN (GRB Coordinate Network) circulars.

- **RXTE**
  The *Rossi* X-ray Timing Explorer (**RXTE**) was launched on December 30, 1995 by a Delta rocket and terminated its operations on January 5, 2012. It was designed to mainly study the temporal and broad-band spectral phenomena associated with stellar and Galactic systems.
  The experiments on board were two narrow field instruments and a wide field detector: the Proportional Counter Array (**PCA**), the High-Energy X-ray Timing Experiment (**HEXTE**), and the All Sky Monitor (**ASM**). The hard X–ray band was covered by the narrow field instruments: PCA (2–60 keV) and HEXTE (17–240 keV).
  The **PCA** (Bradt et al. 1993), designed to measure short-term variability down to μs time scale, consisted of an array of 5 proportional counters. Each counter was an extended version of the successful HEAO-1 A2 HED sealed detector. There were tubular hexagonal collimators providing 1° FOV FWHM. The time resolution was 1 μs.
  HEXTE (Gruber et al. 1996; Rothschild et al. 1998) consisted of 2 independent clusters of 4 NaI(Tl)/CsI(Na) phoswich scintillation detectors, each viewed by a PMT. Around each cluster there were 4 plastic anticoincidence scintillators. The 1° FWHM FOV of each detector was defined by Lead honeycomb collimators. There was a calibration source of ^{241}Am. The time resolution was 10 μs (Bradt et al. 1993).
  Numerous results were obtained with RXTE, demonstrated by thousands of scientific papers. However, many of them have been obtained from the data in the low energy band of PCA (up to 20-30 keV), like the discovery of the kHz QPOs from Low Mass X–ray Binaries (LMXBs) (e.g., van der Klis et al. 1996; van der Klis 1999) that has allowed important astrophysical inferences, like the constraints on mass and radius of neutron stars (Zhang et al. 1997).
  Here, we wish to emphasize some results obtained when the high–energy data are included, either in the entire PCA passband (2–60 keV) or in the PCA plus HEXTE energy band (2–200 keV). During the contemporary operational life of CGRO, RXTE, *BeppoSAX* and INTEGRAL, also coordinated source observations were performed (e.g., the transient 198 s X–ray pulsar

GRO J2058+42, Wilson et al. (1998)) and very broad band spectra could be derived (e.g., GRO J1655−40, Tomsick et al. (1999)).
The results obtained with only RXTE mainly concern temporal and spectral variability of compact Galactic sources in binary systems (mainly LMXBs), from long times scales, like state transitions of BHCs, e.g., Cyg X–1, GRO J1655−40, GX 339−4 (Belloni et al. 1996; Méndez et al. 1998; Smith et al. 1999), down to ms time scales or shorter (e.g., Feng et al. 1999; Gierliński and Zdziarski 2003). Many results concerned the erratic time variability of Black Hole Candidates (BHCs) (e.g., Lin et al. 2000). However, high–energy spectra (>40 keV) could not be determined in the case of weak sources (see, e.g., 47 Tucanae, Ferguson et al. 1999).
In the case of Galactic X–ray sources, several observations concerned the X–ray pulsars, with the discovery of new cyclotron lines, e.g. EXO 2030+375 (Reig and Coe 1999) or their harmonics (e.g. 4U 0115+63, Vela X–1, GX 301−2, MXB 0656−072, 4U 1538−52, Heindl et al. 1999; Kreykenbohm et al. 1999, 2004; McBride et al. 2006; Rodes-Roca et al. 2009).
Many X–ray sources studied with PCA and HEXTE were transient or recurrent transient sources whose outbursts were discovered with the ASM on board. Most of them are compact in binary systems, e.g., XTE J1550−564, whose broad band spectral and temporal behaviour was found similar to that of BHCs (Belloni et al. 2002), XTE J1752−223 new Galactic BH candidate (Shaposhnikov et al. 2010), or the recurrent transient 4U 1608-52, known to be a neutron star in a LMXB (Gierliński and Done 2002). Many Soft X–ray Transients (SXTs) discovered with ASM were followed up with PCA and HEXTE (e.g., Maccarone and Coppi 2003).
In the case of extragalactic sources, different classes were observed in the hard X–ray band and investigated in their spectrum and, in some cases, in temporal variability, from Seyfert galaxies (e.g., McHardy et al. 1999; Lee et al. 1999; Benlloch et al. 2001) to blazars (e.g. Lawson et al. 1999), starburst galaxies (e.g., Gruber and Rephaeli 1999; Rephaeli and Gruber 2002), galaxy clusters (e.g., Coma Cluster, A754, A3667 Rephaeli et al. 1999; Valinia et al. 1999; Rephaeli and Gruber 2004). However, only in the case of bright AGNs, spectral shape could be determined up to 100 keV and beyond (Rivers et al. 2011). In the other cases, the sensitivity limits prevented to give the high–energy spectral shape (e.g., Madejski et al. 1999). A measurement of the CXB spectrum up to 15 keV was also obtained by Revnivtsev et al. (2003), exploiting three years of RXTE/PCA scanning and slewing observations, and using the Earth–viewing data for the estimate of the instrument background.

– **BeppoSAX**
The "Satellite per Astronomia X" (**SAX**) (Boella et al. 1997), result of a collaboration between Italy and the Netherlands, was launched on April 30, 1996 by an Atlas-Centaur rocket and operated until April 30, 2002. After its launch, SAX was renamed **BeppoSAX**, after Giuseppe (diminutive "Beppo") Occhialini.
The experiments on board included Narrow Field (**NFI**) and Wide Field Instruments (**WFI**). The NFIs were four focusing telescopes, three of which (**MECS**) with a 2–10 keV passband and one (**LECS**) with a 0.1–10 keV passband, a High Pressure Gas Scintillation Proportional Counter (**HP-GSPC**) with a 4–120 keV passband, and a Phoswich Detection System (**PDS**) with a 15–200 keV passband. The WFIs were 2 Wide Field Cameras (**WFCs**) with a 2–30 keV passband and a Gamma–Ray Burst Monitor (**GRBM**) with a nominal energy band from 40 to 700 keV. We concentrate on the instruments with passband that covered the hard X–ray band.
HP-GSPC (Manzo et al. 1997) was filled with a high purity gas mixture of Xenon (90%) and Helium (10%) at 5 atm, with a X–ray entrance window of Beryllium. On top of the detector there

was an hexagonal collimator made of Aluminum plus Lead. The entire detector was shielded with Lead plus Tin in all directions other than the FOV. Radioactive sources of ^{55}Fe and ^{109}Cd were adopted for in–flight calibration.

PDS (Frontera et al. 1997b), consisted of a square array of 4 independent and collimated NaI(Tl)/CsI(Na) phoswich scintillation detectors. The collimator assembly consisted of two hexagonal X-ray collimators, one per each pair of detectors, that could be independently rocked back and forth to allow the simultaneous monitoring of source and background. Anticoincidence shields of CsI(Na) surrounded the sides, while a thin plastic scintillator covered the X–ray entrance window. The best time resolution was 16 μs. There was a gain control source of ^{241}Am and a movable calibrator made of a^{57}Co radioactive source distributed along a line.

The 4 lateral and independent shields of PDS were also used as GRB monitor (**GRBM**) in the 40-700 keV energy range with temporal resolution down to 0.5 ms (Frontera et al. 1997b,a; Costa et al. 1998). A trigger system was implemented to identify GRB events. Thanks to the independence of the four scintillators, the instrument was also capable of providing crude GRB locations (within few degrees) (Pamini et al. 1990). Among other things, this feature was of key importance for deriving the photon spectra of the events.

BeppoSAX was designed to perform spectroscopic and time variability studies of celestial X-ray sources and to perform a periodic monitoring of Galaxy plane. However, thanks to the GRBM and WFCs, the GRBM team initiated, since the *BeppoSAX* Science Verification Phase, a search for promptly identifying GRBs with GRBM and accurately localizing them (within a few arcmin) with WFCs. This search, as it is well known, resulted to be very fruitful and conducted to the the first discovery, with the MECS telescopes, of the X–ray afterglow of the 1997 February 28 GRB event (Costa et al. 1997) (see Fig. 14), and, two months later, to the first determination of the GRB redshift (Metzger et al. 1997) and thus of the cosmological distance of their progenitors. These discoveries, whose entire story can be found in Costa and Frontera (2011) and Frontera (2015), made *BeppoSAX* famous. GRB discoveries with *BeppoSAX* continued for its entire operational life time. A summary of the GRB afterglow results can be found in Frontera (2003). A catalog of the 1082 GRBs detected with GRBM and the spectral determination of the brightest ones were also published (Frontera et al. 2009; Guidorzi et al. 2011). In addition to the results on GRBs, the GRBM provided other important results. We mention here the spectral and temporal comparative properties of two large flares from the Soft Gamma-ray Repeater SGR 1900+14 occurred on August 27, 1998 and April 18, 2001 (Guidorzi et al. 2004)

In addition to GRB discoveries, thanks to the very broad passband of the instrumentation (0.1–200 keV), to the well matched sensitivity over the entire band, and to its almost equatorial orbit (PDS, for example, had the lowest background level among all the already flown high–energy instruments), *BeppoSAX* provided key results also in the observations of Galactic and extragalactic sources, for which it was designed. For the first time, the hard X–ray band covered by PDS (>15 keV) was in numerous cases exploited along with the lower energy band, deriving broad band spectra and time variability properties of Galactic and extragalactic sources.

Concerning Galactic sources, significant spectral results were obtained from different classes of sources, either transient or persistent, from supernova remnants, e.g., Cas A (Favata et al. 1997) from which also the detection of the lines at 67.9 and 78.4 keV associated with the nuclear decay of ^{44}Ti was obtained (Vink et al. 2001), to LMXBs, e.g., the dipping source XB 1916−053 (Church et al. 1998), the bursting sources GS 1826−238 (in 't Zand et al. 1999) and 4U 0614+091 (Piraino et al. 1999), the bursting transients SAX J1810.8−2609 (Natalucci et al. 2000b) and SAX J1747.0−2853 (Natalucci et al. 2000a), sources in Globular Clusters, e.g.,

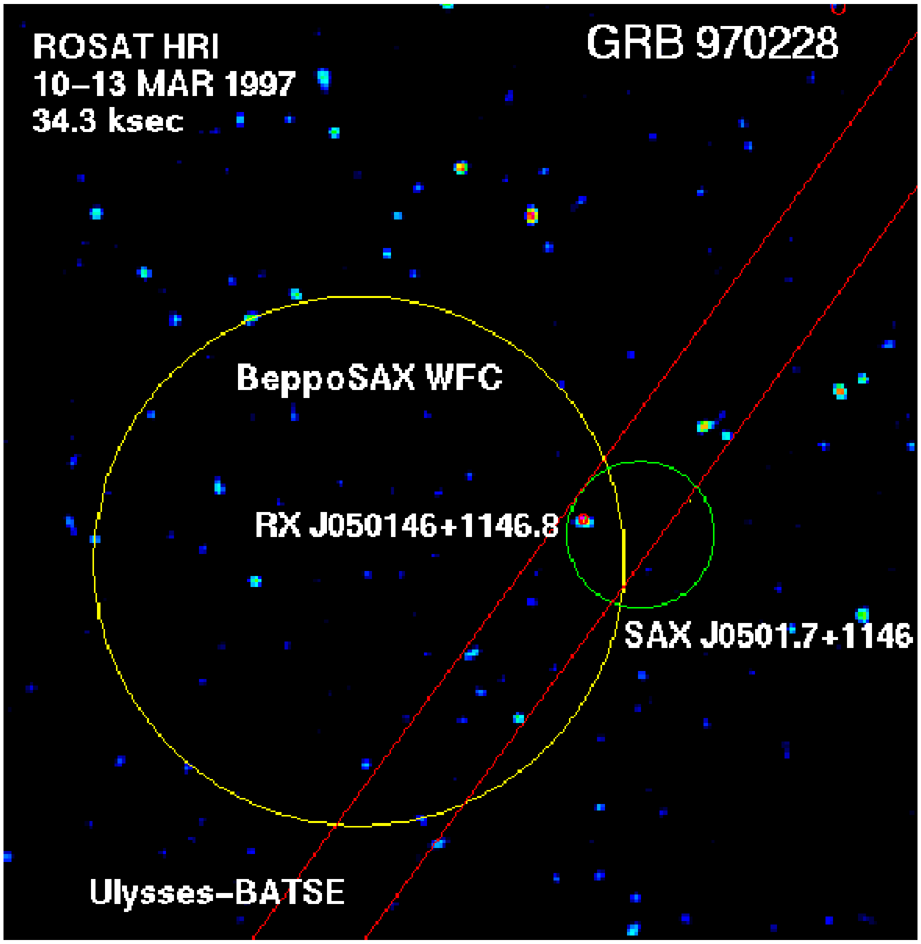

Fig. 14 Localization improvement ladder of the first afterglow source discovered with *BeppoSAX*. *Large circle*: error box of the GRB 970228 event with WFCs, 3 hrs from the event. *Red straight lines:* triangulation annulus derived from *BeppoSAX* and *Ulysses* spacecraft timings (Hurley et al. 1997). *Small circle:* error box of the X–ray afterglow source obtained with MECS 8 hrs from the primary event. *Red dot:* localization uncertainty of the X–ray afterglow source obtained with ROSAT about 12 days from the primary event. The ROSAT position was coincident within 2 arcsec with that of the optical transient associated with GRB970228 (van Paradijs et al. 1997). This result confirmed that X-ray afterglow source and the optical transient were the same object. Reprinted from Frontera et al. (1998).

X 1724−308 in Terzan 2 (Guainazzi et al. 1998), the Rapid Burster (Masetti et al. 2000); BHCs, e.g., 4U 1630−47 (Oosterbroek et al. 1998), the superluminal source in outburst GRS 1915+105 (Feroci et al. 1999), GX 339−4 (Chiappetti et al. 1999), GRS 1758−258 (Sidoli and Mereghetti 2002), the transient in outburst XTE J1650−500 (see Fig. 15) (Montanari et al. 2009), the HMXB Cygnus X–1 in two spectral states (Frontera et al. 2001).
The detection of cyclotron lines, and, in some cases, of their harmonics were found in several X–ray pulsars, e.g. 4U 1907+09 (Cusumano et al. 1998), Vela X–1 (Orlandini et al. 1998b), Cen X–3 (Santangelo et al. 1998; Burderi et al. 2000), 4U 1626−67 (Orlandini et al. 1998a), X 0115+63 from which 4 harmonic features were discovered (Santangelo et al. 1999). A review

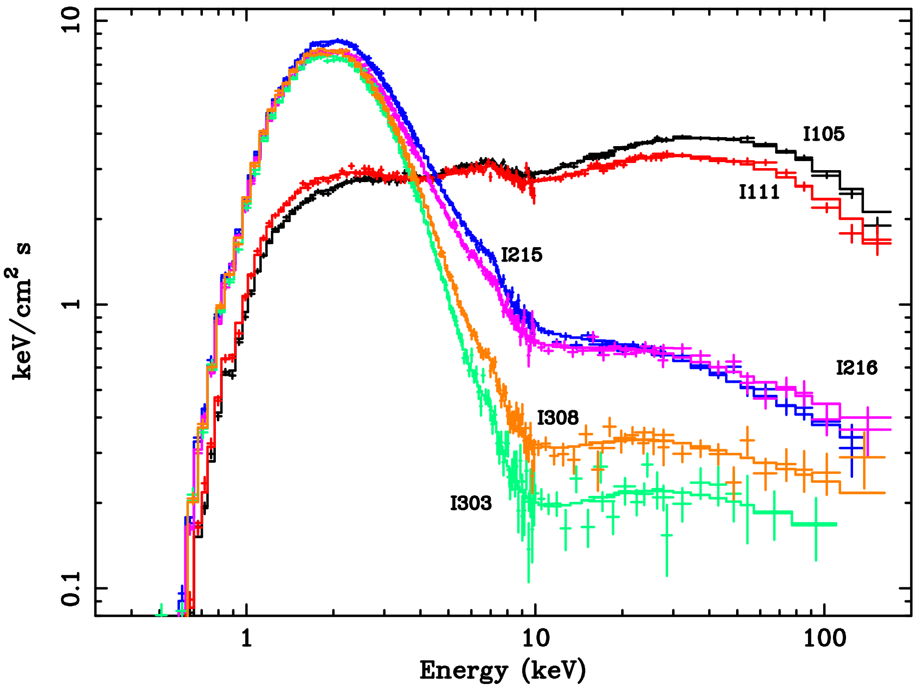

Fig. 15 An example of broad band spectra from celestial X–ray sources obtained with *BeppoSAX*. The figure shows the spectral evolution of the BHC transient XTE J1650−500 observed with *BeppoSAX* at different times during an outburst. Reprinted from Montanari et al. (2009).

of the broad–band spectra of accretion–powered X–ray pulsars observed with *BeppoSAX* was done by dal Fiume et al. (2000).
Concerning extragalactic sources, significant broad band spectra had been derived from different classes, from BL Lac objects/blazars, e.g. PKS 2155−304 (Giommi et al. 1998), Mkn 421 (Guainazzi et al. 1999c; Malizia et al. 2000), Mkn 501 (Pian et al. 1998), NGC 7674 (Malaguti et al. 1998), ON 231 (Tagliaferri et al. 2000), PKS 0528+134 (Ghisellini et al. 1999), to LINER galaxies, e.g. NGC 3998 (Pellegrini et al. 2000), to Seyfert 1 galaxies, e.g. NGC 4593 (Guainazzi et al. 1999b), NGC 2110 (Malaguti et al. 1999), to Seyfert 2 galaxies, e.g. NGC 1068 (Matt et al. 1997), NGC 2992 (Gilli et al. 2000), MCG −6−30−15 (Guainazzi et al. 1999a), Mkn 3 (Cappi et al. 1999), to quasars, e.g. 3C 373 (Grandi et al. 1997), the high redshift quasar PKS 2149−306 (Elvis et al. 2000), to hard X–ray radiation from galaxy clusters, e.g. Coma Cluster (Fusco-Femiano et al. 1999), A 2256 (Fusco-Femiano et al. 2000) and Centaurus Cluster (Molendi et al. 2002).
Also, the hard X–ray spectrum up to 60 keV and the absolute intensity of the cosmic X–ray Diffuse Background was investigated with the PDS with significant results (Frontera et al. 2007).

3.3.2 Balloon Experiments

– **GRIS 1992**
We have already discussed the GRIS experiment. A larger configuration was again launched two times in 1992 (Leventhal et al. 1993). The number of detectors was still 7, but they were made

of the largest available high–purity Ge (detector volume of about 2000 cm^3). The instrument was capable to point to a source with an accuracy of a few tenths of degree.
A full Galactic center transit of 12 hr duration was achieved in both flights. The result was the detection of the electron/positron annihilation line in both flights, with a 511 keV flux of $(7.7 \pm 1.2) \times 10^{-4}$ and $(8.9 \pm 1.1) \times 10^{-4}$ photons/(cm^2 s), respectively. It was the first time that successive high-resolution balloon measurements were achieved on a time scale of days.

– **LXeGRIT**
The Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT), a result of a collaboration led by the Columbia University Laboratory, was flown in 1989 and 1999 from Fort Sumner (Aprile et al. 2004). The main instrument (Aprile et al. 2000; Oberlack et al. 2000) consisted in a large-volume liquid Xenon Compton telescope based on full event imaging in a time projection chamber. It imaged gamma-rays in the energy range from 200 keV to 25 MeV, with an angular resolution of 3° at 1.8 MeV. The flights, part of which was spent to observe the Crab Nebula, were mainly used to estimate the experiment performance (imaging and spectroscopy) (Aprile et al. 2003, 2004).

– **Tata Institute experiment**
A balloon experiment successfully flown several times between 1985 and 1992, with the observation of several X–ray Binaries (e.g., 4U 1907+09, GX 1+4 (Chitnis et al. 1993), Cygnus X-3 (Rao et al. 1991)) was that developed at the Tata Institute for Fundamental Research (TIFR) in Bombay (India) (e.g., Chitnis et al. 1993). The telescope consisted of two collimated large–area Xenon–filled multi-anode proportional counters. The detection efficiency was $\geq 50\%$ between 20 and 80 keV.

3.4 2000s missions and balloon experiments

The satellite missions launched in this decade are characterized by broad energy band and imaging capabilities, also in hard X–rays (e.g., *INTEGRAL*). Two of these missions, *HETE 2* and the still operational *Swift*, were specifically designed for GRB studies. But, also the high–energy gamma–ray missions *Fermi* and *AGILE* were designed taking into account specific GRB detections.

Concerning balloon experiments, this decade sees the design and development of hard X–ray polarimeters, e.g., HX-POL (Krawczynski et al. 2009), POGOlite (Pearce et al. 2008), GRAPE (Bloser et al. 2006) and, for the first time, the first test flights of hard X–ray focusing telescopes (see below).

3.4.1 Satellite missions

– **HETE 2**
The High–Energy Transient Explorer 2 (HETE-2) (Ricker et al. 2003) was launched on October 9, 2000 by a Pegasus rocket and terminated in March 2008. It was designed to detect GRBs, determine their properties with simultaneous observations at soft, medium and high–energy X-rays, and to provide within several seconds their precise localization. The instruments onboard were a Soft X–ray Camera (**SXC**; 0.5–10 keV; Villasenor et al. 2003)), a Wide-Field X–Ray Monitor (**WXM**; 2-20 keV; Kawai et al. 2003) and a FREnch GAmma–ray TElescope (**FREGATE**; 6–400 keV Atteia et al. 2003). We limit our description to FREGATE.

FREGATE was a classical hard X–ray/soft gamma–ray detector with the main task of alerting the other instruments of the occurrence of a GRB. It was made of 4 NaI(Tl) scintillation cleaved crystals. The instrument worked well for the entire operational mission life time.
Among the most significant results of HETE 2 there was the discovery of the first GRB (030329) (Vanderspek et al. 2003) unambiguously associated with a supernova (Stanek et al. 2003), confirming the association of the *BeppoSAX* GRB 980425 with the supernova SN1998bw (Galama et al. 1998). Another outstanding result was the study of X-Ray Flashes (XRF), a class of events discovered with *BeppoSAX* (Heise et al. 2001). With HETE 2 it was possible to establish that XRFs and X–ray rich events are less energetic subclasses of GRBs, establishing that all three kinds of bursts (GRB, XRF, XRR) arise from the same phenomenon (e.g., Sakamoto et al. 2005). Another important result, soon after confirmed with the *Swift* satellite (see below), was the apparent detection of an extended emission after short GRBs (Villasenor et al. 2005), confirming the results found with BATSE (e.g., Lazzati et al. 2001) and *BeppoSAX* GRBM (Montanari et al. 2005).

– **INTEGRAL**
The INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) was launched on October 17, 2002 by a Proton rocket and it is still operational. It was designed to produce a complete map of the sky in the hard X–ray/soft gamma–ray band.
The main experiments on board are a Gamma-ray Spectrometer (**SPI**) and a Gamma-ray Imager (**IBIS**).
SPI (Vedrenne et al. 2003; Roques et al. 2003) consists of an array of 19 n-type Ge cooled detectors with hexagonal shape, surrounded by an active anticoincidence shield of BGO. The energy passband is 20 keV-8 MeV. An active cryogenic system guarantees a temperature of the Ge detectors at 85 K. A Tungsten coded aperture mask located 1.7 m from the Germanium array provides an angular resolution of 2.5° (FWHM) in its FOV. The mask geometry is circular with 127 hexagonal pixels, of which 63 are opaque. To further reduce the background, a plastic scintillator is located below the mask.
IBIS is a coded aperture mask gamma-ray telescope sensitive to the 15 keV-10 MeV energy range (Ubertini et al. 2003). The detector assembly has two position-sensitive detection planes: a) a front layer (**ISGRI**; Lebrun et al. 2003) of CdTe pixels with a passband of 15 keV-1 MeV; and b) a back layer (**PICsIT**; Di Cocco et al. 2003) of CsI(Tl) pixels with a passband of 170 keV-10 MeV.
The separation between the detecting planes is about 94 mm, so IBIS can also work as a Compton telescope. An anticoincidence shield made of BGO crystals read out by PMTs is around the detector. The coded mask is located 3.2 m above the collimated detection plane and provides an angular resolution of 12 arcmin.
Many relevant results have already been obtained with INTEGRAL on both Galactic (mainly compact objects) and extragalactic (mainly AGNs) sources. We mention here the most relevant ones. One of them certainly concerns the discovery of highly obscured ($N_H > 10^{23}$ cm^{-2}) super–giant High Mass X–ray Binaries (sgHMXBs) (see, e.g., the review by Walter et al. (2015)). From the same class of sources, INTEGRAL also discovered fast X-ray outbursts lasting less than a day, typically a few hours, now known as Super-giant Fast X–ray Transients (SFXT) (Sguera et al. 2005, 2006).
Another very important result obtained with INTEGRAL plus the HEXTE instrument aboard RXTE is discovery of unexpected hard spectral tails (>10 keV) in the total and pulsed spectra

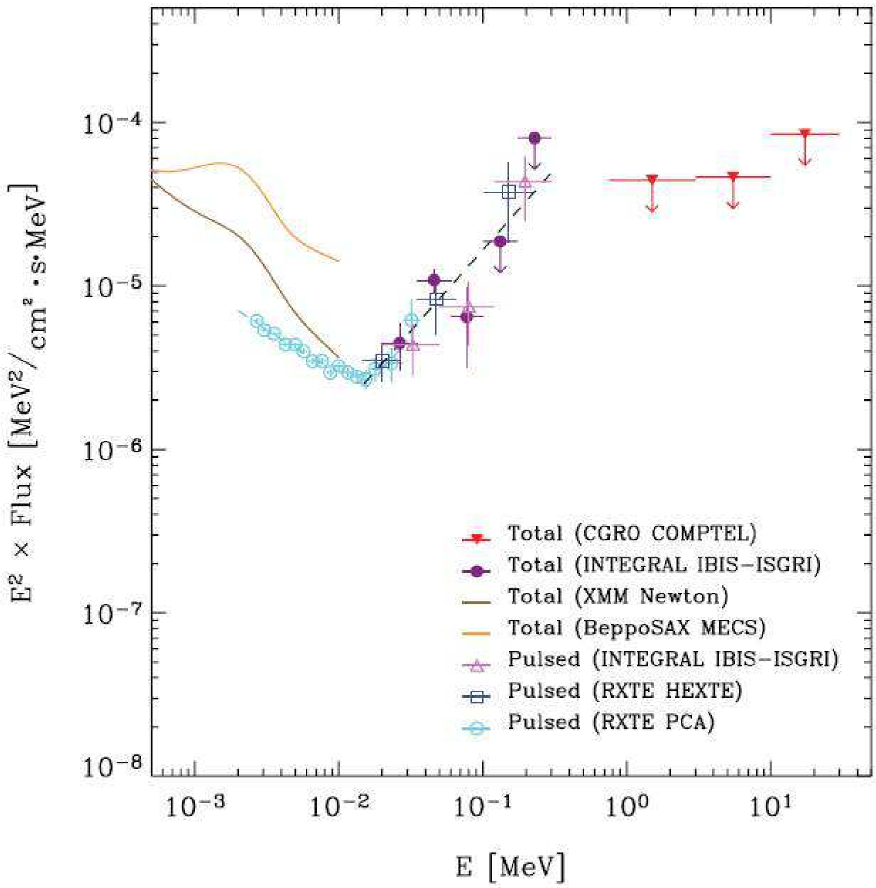

Fig. 16 Discovery of a high–energy component from Anomalous X–ray Pulsars. The figure shows the hard X–ray energy results obtained with *INTEGRAL* ISGRI and *Rossi XTE* HEXTE for the AXP RXS J1708−4009. Note the upper limits above 100 keV up to the energy band covered with *Compton Gamma–Ray Observatory* COMPTEL. Reprinted from Kuiper et al. (2006).

of Anomalous X–ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) (see, e.g., Fig. 16) (Kuiper et al. 2004, 2006, 2008; Götz et al. 2006). Theoretical interpretations have been advanced (e.g., Beloborodov 2013), but, due to sensitivity limitations, the shape of the hard tails is still undefined above 100 keV.

Thanks to its wide field of view, its imaging capability and its long operation (more than 10 years), INTEGRAL has allowed the first complete hard X–ray sky survey after that performed with HEAO–1 A4 (see above). The most recent survey in the 17–100 keV energy band is that reported by Bird et al. (2016), while at energies beyond 100 keV see Krivonos et al. (2015).

Another outstanding INTEGRAL result is the measurement of polarized radiation. Polarized hard X–ray photons (>200 keV) have been measured from the Crab Nebula at an angle parallel to the pulsar rotation axis (Dean et al. 2008; Forot et al. 2008). Strongly polarized radiation (polarization fraction of 67±30%) has also been detected in the 400 keV–2 MeV energy band

from Cygnus X–1 (see Fig. 17), revealing that the MeV emission is probably related to the jet first detected in the radio band (Laurent et al. 2011b; Jourdain et al. 2012). Also from several GRBs a significant level of polarized radiation has been detected with INTEGRAL (Götz et al. 2009, 2013, 2014).
For the first time INTEGRAL allowed to measure the space distribution of the 511 keV positron annihilation line from the Galactic Center region. However, while Weidenspointner et al. (2008) reported an asymmetric disk emission, Bouchet et al. (2009) showed an emission symmetric with respect to the Galactic Center. This result is very important to understand the origin of the Galactic positron population and numerous papers were triggered by these observations. Different potential sources of positrons were suggested, like Sgr A, pulsars, binaries, sources of radioactive elements like ^{26}Al, ^{56}Co, ^{44}Ti, dark matter.
Detection with INTEGRAL of a 511 keV emission line has also been recently reported by Siegert et al. (2016) from the microquasar V404 Cygni. This observation follows the emission line observation around 500 keV from the X–ray Nova in Musca with SIGMA, discussed above (Goldwurm et al. 1992). These results support the conjecture that the diffuse emission of annihilation gamma–rays in the Bulge region of our Galaxy could be due to microquasars.
Another peculiar result concerns the detection of hard X–ray lines. INTEGRAL detected the lines at 67.9 and 78.4 keV associated with the nuclear decay of ^{44}Ti from the remnant of the supernova 1987A (Grebenev et al. 2012). From the measured fluxes it was possible to establish that this decay provided sufficient energy to power the remnant at late times. The initial mass of ^{44}Ti was estimated to be $(3.1 \pm 0.8) \times 10^{-4}$ M$_\odot$, which is near the upper bound of theoretical predictions (Grebenev et al. 2012). Another relevant result is the first ever detection of the gamma–ray lines at 847 keV and 1238 keV in the spectrum of the SNIa SN2014J. From the line fluxes it was possible to establish that 0.62 ± 0.13 M$_\odot$ of radioactive ^{56}Ni was synthesized during the explosion (Churazov et al. 2014).

– **Swift**
The *Swift* Gamma-ray burst Explorer was launched on November 20, 2004 by a Delta rocket and it is still operational. It was designed mainly for studying the early afterglow of GRBs. For that purpose it includes a Burst Alert Telescope (**BAT**) for detecting and locating GRBs, an X-ray Telescope (**XRT**, 2–10 keV) and a UV/Visible light telescope (**UVOT**) for promptly detecting and monitoring their X–ray and optical afterglow. In addition, the GRB coordinates are promptly distributed for giving the opportunity of prompt multi-wavelength observations from the ground. We concentrate on the hard X-ray experiment BAT.
BAT is a hard X–ray telescope with a passband from 15 to 150 keV that makes use of a coded mask system to locate celestial sources (Barthelmy et al. 2005). In its passband, it achieves an angular resolution of 20 arcmin, with a location capability of 1.4 arcmin. The detector is an array of Cd(Zn)Te crystals, positioned 1 m below the mask. The mask is made of Lead tiles distributed in a half-filled random pattern. To reduce the background a graded shield is located on the side walls between the mask and the detector plane and under the detector plane. BAT observes 88% of the sky every day with a detection sensitivity of 5.3 mCrab for a full-day observation (Krimm et al. 2013).
Among the numerous *Swift* results on GRBs (see, e.g., the review by Gehrels and Razzaque (2013)), we wish to mention the detection of the most distant long GRB (090429B, z$\sim$9.4) (Cucchiara et al. 2011), the first accurate localization and redshift measurement of a short burst (Gehrels et al. 2005), the detection so far of more than 1000 GRBs (1080 GRBs in September

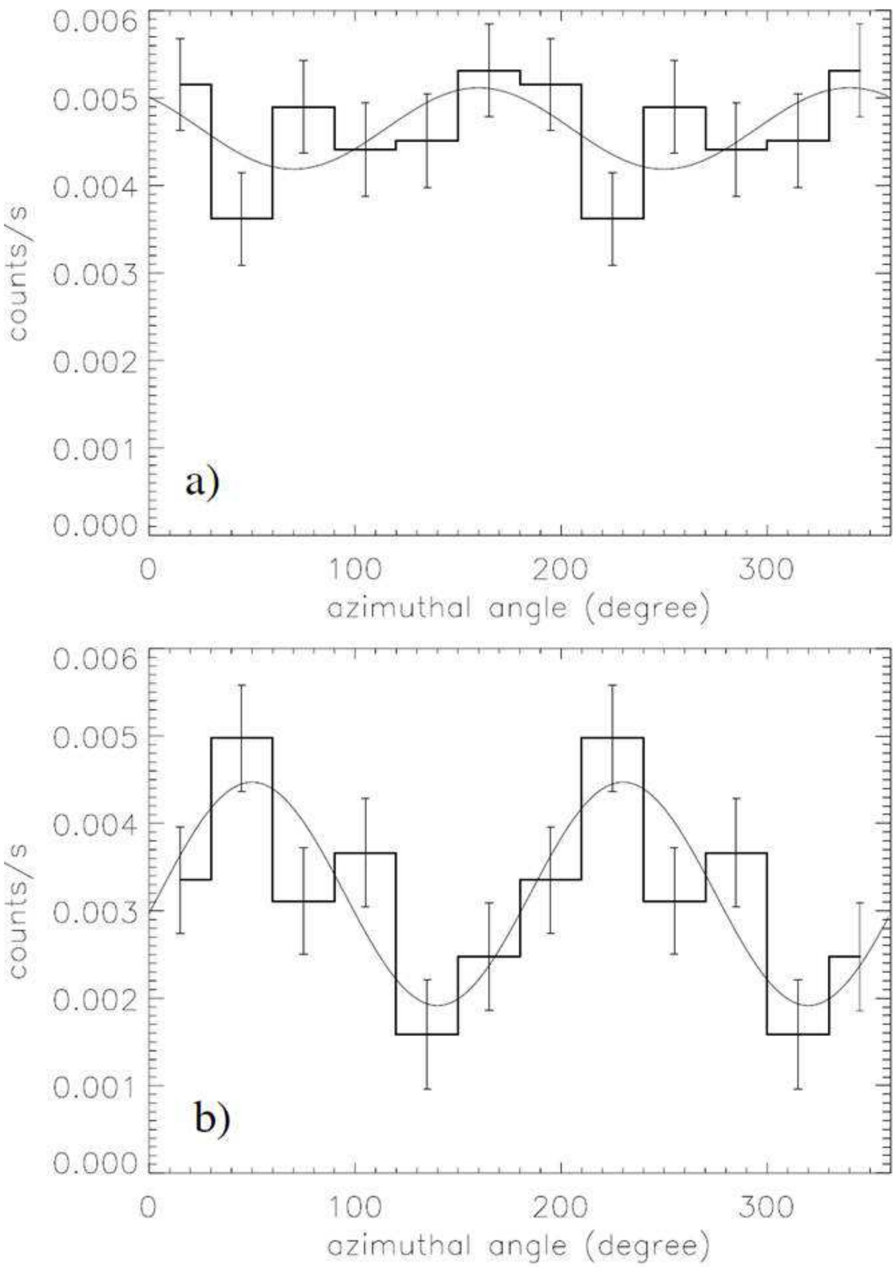

Fig. 17 Discovery of polarized soft gamma–ray radiation from Cygnus X–1 with *INTEGRAL*. The polarization signal is negligible in the energy in the 250–400 keV energy band (panel a), but it becomes detectable (polarization fraction $= 67 \pm 30$ %) at higher energies (400–2000 keV; panel b). Reprinted from Laurent et al. (2011a).

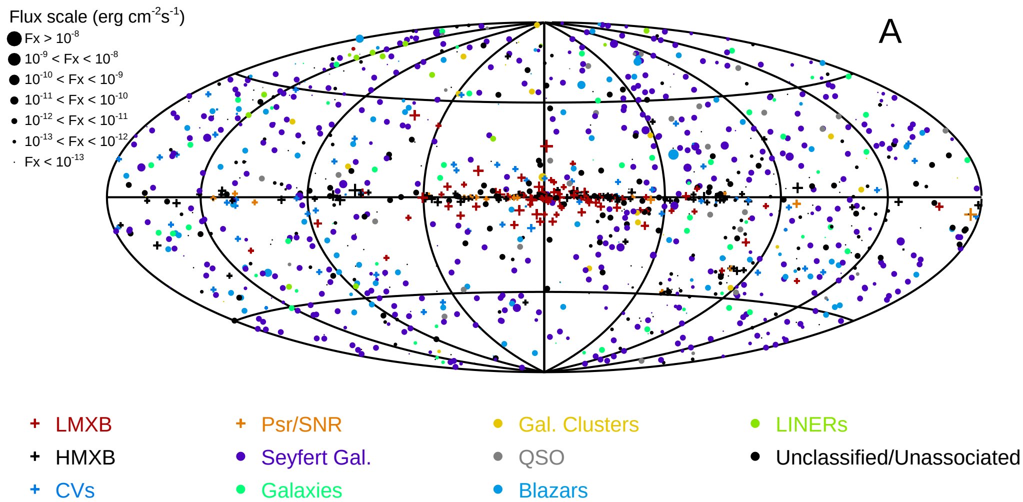

Fig. 18 The hard X–ray (15–150 keV) sky in Galactic coordinates obtained with the BAT telescope aboard *Swift* down to a flux level of 10^{-13} erg cm^{-2} s^{-1}. The size of the symbols is proportional to the flux in 15–150 keV, while the different colours specify the object class according to the legend in the bottom of the figure. Reprinted from Cusumano et al. (2010).

2016), with about 1/3 with known redshifts. In addition to the GRB discoveries, BAT has allowed many significant results on other celestial phenomena and sources. Among them, we mention the discovery of Tidal Disruption Flares (TDFs) with relativistic outflow, like that occurred on 2011 March 28 (e.g. Burrows et al. 2011; Bloom et al. 2011). BAT has already been a rich source of discovery of new Galactic and extragalactic sources and has provided light curves for several hundred hard X-ray sources (Krimm et al. 2013). Among the Galactic sources, the most interesting objects discovered and/or monitored and are certainly the several magnetars (see, e.g., Rea and Esposito 2011; Rea et al. 2012) and SFXTs (e.g. Romano et al. 2014). Thanks to the daily survey of 88% of the sky, a source catalog of the entire sky, in particular of the high Galactic latitude sky, has been possible (e.g., Cusumano et al. 2010) (see Fig. 18). Also deep surveys, down to ∼1mCrab level, have been performed with the goal of establishing the nature of the source population responsible for the CXB at hard X–ray energies (e.g., Ajello et al. 2008a). Also, it was possible to derive the CXB spectrum at hard X–ray energies with the BAT (Ajello et al. 2008b).

– **SUZAKU**
Also known as **Astro-E2**, the fifth Japanese X-ray astronomy satellite **SUZAKU** was launched on July 10, 2005 by a M-5 rocket and came to an end on September 2, 2015. As the failed mission Astro-E, it was designed to obtain precise measurements of high-energy processes in stars, supernova remnants, galaxies, clusters of galaxies, and the environments around neutron stars and black holes.
The satellite carried three experiments on board (Inoue 2003): an X-ray Imaging Spectrometer (**XIS**) consisting of four imaging CCD cameras sensitive in the 0.2-12.0 keV band, each located at the focal plane of a dedicated X-ray telescope. The second was a non-imaging, collimated Hard X-ray Detector (**HXD**) sensitive in the 10-600 keV band. The third instrument would

have been an X-ray micro-calorimeter (X-ray Spectrometer (**XRS**), but it lost all of its cryogen before scientific observations could begin. We concentrate here on the hard X–ray instrument.
HXD (Takahashi et al. 2007) consisted of an array of 16 (4 × 4) phoswich counters located under Silicon PIN diodes, which in turn were surrounded by BGO anti-coincidence well-type shields that had also the role of active gross collimators (Takahashi et al. 2007). Each phoswich counter was a Gadolinium Silicate crystal (GSO; $Gd_2SiO_5(Ce)$) optically coupled with a BGO crystal. The PIN diodes absorbed X-rays with energies below 70 keV, but gradually became transparent to harder X–rays, which in turn reached and were detected by the GSO detectors. Passive collimators defined the instrument FOV, which was narrow below 100 keV and broader at higher energies (see Table 1). The time resolution was 61 μs (Mitsuda et al. 2007).
The lateral anticoincidence shield counters of BGO were also used as a Wide-band All-sky Monitor (**WAM**) to detect GRBs in the 50 keV-5 MeV range. The WAM FOV was about 2π with an effective area of 800 cm^2 at 100 keV and 400 cm^2 at 1 MeV (Mitsuda et al. 2007). The WAM had a time resolution of 31.25 ms when it was triggered by a GRB and of 1 s in the waiting time (Mitsuda et al. 2007).
Numerous interesting results were obtained with *Suzaku*. Many of them include data from the **HXD**, providing broad band spectra from 0.7 keV up to hard X–ray energies. They concern Galactic and extragalactic objects. Among the latter, significant results were obtained from AGNs, like the Seyfert 1 galaxy NGC 3516 (Markowitz et al. 2006) and MCG−6−30−15 (Miniutti et al. 2007), the obscured Seyfert 1.9 MCG −5−23−16 (Reeves et al. 2007), the very obscured Seyfert 2 NGC 4945 (Itoh et al. 2008), NGC 2273 (first detection of hard X–rays) (Awaki et al. 2009), and NGC 4388 (Shirai et al. 2008), the quasars PKS 1510−089 (Kataoka et al. 2008), the TeV blazars 1ES 1101−232 and 1ES 1553+113 (Reimer et al. 2008), the high redshift ($z = 2.69$) flat-spectrum radio quasar (FSRQ) RBS 315 (Tavecchio et al. 2007), the Compton-thick (column density $> 10^{24}$ cm^{-2}) AGN NGC 1365 (Risaliti et al. 2009).
Also, spectra of galaxy clusters extended up to hard X–ray energies were reported, like that from Ophiuchus, one of the hottest cool core clusters (Fujita et al. 2008), that from the merging cluster Abell 3667 (Nakazawa et al. 2009) and that from Abell cluster A2163, found to be the hottest ($kT \sim 14$ keV) (Ota et al. 2014).
Significant diffuse hard X–ray emission was detected for the first time from the Galactic Center (Yuasa et al. 2008). Among the broad band spectra of Galactic X–ray sources extending up to hard X–ray energies, we mention the nice results obtained from the black-hole binaries GRO J1655−40 (Takahashi et al. 2008) and GRS 1915+105 (Ueda et al. 2010), those obtained from the supernova remant RX J1713.7−3946 (Takahashi et al. 2008; Tanaka et al. 2008), the discovery of photons up to 70 keV from a classical nova (V2491 Cygni) (Takei et al. 2009), the broad–band spectra from Anomalous X–ray Pulsars (AXP) and Soft Gamma–ray Repeaters (SGR), with the strong confirmation of a hard X–ray tail in the persistent spectra from AXP 1E 1547.0−5408 (Enoto et al. 2010) after its discovery with the INTEGRAL satellite (Baldovin et al. 2009), the discovery of a hard tail during short bursts from SGR 0501+4516 (Nakagawa et al. 2011), and the first detection of hard X–rays from an Ultra Luminous Source (ULX) (M82 X–1, Miyawaki et al. 2009).
Also cyclotron resonance scattering features (CRSF) in X–ray pulsars were investigated, like that from A 0535+26 during a very low luminosity state of the source (Terada et al. 2006), the discovery of a second harmonic at 72 keV from Her X–1 (Enoto et al. 2008), the discovery, in collaboration with *Rossi XTE*, of a CRSF at 54 keV from GX 304−1 (Yamamoto et al. 2011), the first discovery of an absorption feature at 15 keV from a SFXT (AX J1841.0−0536,

Kawabata Nobukawa et al. 2012), the first firm detection of a CRSF at 76 keV in the X-ray spectrum of the Be X-ray binary pulsar GRO J1008-57 (Yamamoto et al. 2014).
Also, hard X–ray spectral properties from symbiotic stars have been derived, e.g., SS73 17 (Smith et al. 2008).
Interesting observations concern the identification of the nature of sources found with all–sky surveys performed with *INTEGRAL* IBIS and *Swift* BAT (e.g., Morris et al. 2009). An interesting case is that of XSS J12270−4859 that was initially classified as an Intermediate Polar, while, thanks to the broad band spectra obtained with *Suzaku*, the source turned out to be a LMXB harbouring a milli-second pulsar, which switches between an accretion-powered state (LMXB) and a rotation-powered pulsar state (a so-called transitional pulsar).
Also the WAM instrument provided significant hard X-ray spectral results on GRB prompt emission (e.g., Ohno et al. 2008).

– **AGILE**
AGILE (Astrorivelatore Gamma a Immagini LEggero) is an Italian mission, launched on 2007 April 23 by a PSLV-CA indian rocket and it is still operational. The mission is devoted to high–energy gamma-rays (>100 MeV), but it includes a hard X-ray monitor, **SuperAGILE** (Feroci et al. 2007), devoted to monitor the hard X–ray sky in the 15–45 keV energy band with an on-axis angular resolution of 6 arcmin. SuperAGILE is composed by 4 Silicon-microstrip detectors coupled with a set of mutually orthogonal one-dimensional coded masks (Feroci et al. 2007). Mask and detector have the same size and are 142 mm far away. The instrument has a source location accuracy of 2-3 arcminutes. A segmented anti-coincidence system made of plastic shield surrounds all detectors.
Various results of the SuperAGILE monitor have been reported. We mention here the review of various classes of sources detected in the first two years (Feroci et al. 2010), the one-year continuum monitoring of the X–ray pulsar of GX 301−2 (Evangelista et al. 2010).

– ***Fermi* gamma–ray space telescope**
The ***Fermi* gamma–ray space telescope**, formerly called **GLAST** (**Gamma-ray LArge Space Telescope**), was launched on June 11, 2008 by a Delta II rocket and it is still operational. It was designed mainly to survey high–energy gamma–rays (20 MeV–300 GeV) from astronomical sources. It also includes a hard X-ray experiment, the Gamma-ray Burst Monitor (**GBM**), designed to detect GRBs in the 10 keV-30 MeV energy range, with the goal of extending down the energy band covered by the Large Area Telescope (**LAT**) and of computing prompt burst locations onboard to allow re-orienting of the LAT to observe the delayed emission from the located GRBs.
The **GBM** (Meegan et al. 2009) consists of an array of 12 thin disks of NaI(Tl) oriented in 12 different directions and 2 BGO scintillation detectors. The main features of GBM are given in Table 1. Each NaI crystal is packed in an hermetically sealed Aluminum-housing with a thin window (0.2 mm thick Beryllium). The BGOs are mounted on opposite sides. The best time resolution is 2 μs in time-tagged event (TTE) mode.
Many GRBs are being detected with GBM, of which the brightest ones could be crudely localized (within a few degrees), too coarse for follow-up at longer wavelengths. Instead GBM has the advantage, with respect to Swift/BAT, of a broad passband. In addition to GRB catalogs (e.g. von Kienlin et al. 2014), many accurate spectral studies of the GRB prompt emission have

been performed (e.g., Guiriec et al. 2010; Gruber et al. 2011; Nava et al. 2011), with significant results, like the detection of a blackbody component in the spectra of GRBs in addition to the non-thermal one (e.g., Guiriec et al. 2011). Other significant results of GBM concern the spectral and temporal properties of Terrestrial Gamma–ray Flashes (TGFs) (e.g., Briggs et al. 2010).

In addition to the results obtained on GRBs and TGFs, important results obtained with GBM concern the long monitoring and discovery of variable sources like X–ray pulsars and magnetars (AXPs, SGRs). In addition, through the Earth occultation technique it is possible to perform a long duration monitoring of persistent hard X–ray sources. Examples of these results are the discovery of a new SGR (van der Horst et al. 2010), the discovery of a new torque reversal and spin-up of the X–ray pulsar 4U 1626−67 when GBM data are combined with those from Swift/BAT (Camero-Arranz et al. 2010), the spectral and temporal studies of SGRs, like SGR J1550−5418 (=1E 1547.0−5408) (Kaneko et al. 2010), the light-curve of hundreds of strong X–ray/soft gamma–ray Galactic and extragalactic sources (Wilson-Hodge et al. 2012), the hard X–ray study of thermonuclear bursts, e.g. from the NS low-mass X-ray binary 4U 0614+09 (Linares et al. 2012). Very important was a 7% decline of the Crab Nebula flux (nebular component) in the 15–50 keV band, observed over two years, from 2008 to 2010 and confirmed by other instruments (Wilson-Hodge et al. 2011).

3.4.2 Balloon experiments

The most significant balloon experiments launched in the 2000s decade are reported below.

– **HERO**

  The High-Energy Replicated Optics (HERO) experiment (Ramsey et al. 2002; Iniewsky 2010) was the first experiment flown with focusing optics (FO). It was flown in 2001 on a stratospheric balloon from Fort Sumner for 17 h.

  It consisted of 2 co-aligned mirror modules, each module containing 3 nested mirror shells, sensitive in the 20-45 keV energy range, providing an angular resolution better than 45 arcseconds Half-Power Diameter (HPD). The focal-plane detector was a Gas Scintillation Proportional Counter (GSPC), filled with Xenon-Helium mixture at a total pressure of 10 atm, with 350 μm spatial resolution.

  The hard X-ray optics were made of full-shell electroformed-nickel-replicated mirrors (0.25 mm thick) coated with 50 nm Iridium to enhance the high-energy reflectivity. The mirrors were conical approximations to a Wolter I geometry, with a monolithic shell structure containing both parabolic and hyperbolic segments. The mirrors had a 3 m focal length.

  The balloon experiment was successful and, for the first time, hard X–ray images of the Crab Nebula plus its pulsar, Cygnus X-1 and GRS 1915+105, were obtained (Ramsey et al. 2002).

– **CLAIRE**

  CLAIRE was an experiment flown on 2000 June 15 and on 2001 June 14 from Gap-Tallard (France), with the primary objective of testing a narrow band gamma–ray lens under space conditions. Scientific results were obtained in the second flight (Halloin et al. 2003; von Ballmoos et al. 2005).

The lens had a diameter of 45 cm (8 crystal rings) and a focal length of 279 cm. It consisted of 556 $Ge_{0.98}Si_{0.02}$ flat Germanium-rich mosaic crystals with two different sizes (1×1 cm^2 and 1×0.7 cm^2) disposed on 8 concentric rings. The crystals were properly oriented to focus only photons within a bandwidth of 3 keV centred at 170 keV. The expected focal spot was 1.5 cm diameter. In the focal plane there was a detector made of a 3×3 array of High Purity Germanium (HPGe) crystals with 1.5×1.5 cm^2 cross section, cooled by a liquid Nitrogen criostat. The detector was actively shielded by a CsI(Tl) side shield and BGO collimators.
The 2001 experiment pointed the Crab nebula for 72 minutes, collecting 33 photons in the 3 keV bandpass of the lens, consistently with those expected (von Ballmoos et al. 2005).

– **InFOCμS**
Another balloon experiment with a hard X–ray focusing telescope was the International Focusing Optics Collaboration for μCrab Sensitivity (InFOCμS), led by Nagoya University in Japan (Tawara et al. 2001). It was flown from Fort Sumner (USA) in 2004 for 22.5 hrs.
The hard X-ray telescope consisted of a depth-graded Platinum/Carbon multilayer mirror and a CdZnTe (CZT) focal plane detector. The telescope, using the conical approximation to the Wolter I geometry, consisted of 255 nested mirrors with a focal length of 8 m (Tawara et al. 2001). It was sensitive in the 20-40 keV energy range, with an angular resolution of 2.4 arcminutes (HPD). The pixellated planar CdZnTe detector was configured with a 12×12 segmented array of detection pixels of 2 mm^2 cross section (Baumgartner et al. 2003). The detector was surrounded by a 3 cm thick CsI anticoincidence active shield to reduce background from particles and photons.
The Cygnus X-1 image and spectrum were obtained in spite of an instability of the pointing system (Baumgartner et al. 2003).

– **HEFT**
Also the High–Energy Focusing Telescope (*HEFT*) was a balloon-borne experiment with a hard X–ray focusing telescope on board. It was the result of an international collaboration led by the Columbia University and CalTech. It was flown on May 18, 2005 from Fort Sumner (New Mexico) for a total of 25 hrs at a floating altitude of about 40 km. It consisted of an array of 3 co-aligned conical-approximation Wolter I mirrors (Koglin et al. 2006), each of which focusing hard X–rays (6–68 keV) onto a focal plane well shielded, solid-state CZT pixel detector. Each telescope module contained 72 mirror shells, each divided into 5 mirror segments. The mirror modules were made of a glass substrate with depth-graded W/Si and Ni/Si multilayers (Harrison et al. 2000). The focal length was of 6 m, and the angular resolution (HPD) in its FOV was 1 arcmin. During the flight, successful observations of celestial objects as Crab Nebula, Cyg X-1, Her X-1, GRS 1915 and X-Persei (Koglin et al. 2006), and the simultaneous observation with Swift of the Blazar 3C454.3, were performed. However, the results were only presented at conferences with no proceedings (e.g., Chen et al. 2006). The successful flight of *HEFT* was important for the design of the **NuSTAR** mission (see below).

– **ProtoEXIST1**
ProtoEXIST1 was a balloon experiment devoted to qualify the technology required for the High–Energy Telescope (HET) of the Energetic X-ray Imaging Survey Telescope (EXIST) mission proposal. It was launched from the Columbia Scientific Balloon Facility at Ft. Sumner in 2009 (Hong et al. 2011).

It was a wide-field hard X-ray coded-aperture telescope in the 30-600 keV band. The detector plane consisted of an 8×8 array of pixellated CZT crystals mounted on a set of readout electronics boards. A tungsten mask, mounted at 90 cm above the detector, provided shadowgrams of the X–ray sources with an angular resolution of 20 arcmin in its FCFOV of 9° × 9° (see Table 2).
In order to reduce the background radiation, the detector was surrounded by passive shields on the four sides all the way to the mask. On the back side of the detector, a CsI(Na) active anticoincidence shield provided signals to tag charged particle induced events as well as ≥100 keV background photons from below.
During the flight the BHC Cygnus X–1 was observed for 1 hr, obtaining its image and hard X–ray spectrum (Hong et al. 2011).

3.5 **2010s satellites and balloon experiments**

The today effort in hard X–ray/soft gamma–rays is mainly devoted to significantly increase the instrument sensitivity and its angular resolution. This can be obtained by means of focusing techniques. **NuSTAR** is the first launched space mission devoted to this objective although the energy band is limited to 80 keV. A focusing optics telescope sensitive up to 80 keV and a and a non-focusing telescope sensitive up to 600 keV were also part of the **ASTRO–H** payload (Takahashi et al. 2014). Unfortunately, after a successful Science Verification Phase, this mission, launched on Feb. 17, 2016 and later renamed to **Hitomi**, was lost on March 29, 2016 at the beginning of the Operational Phase due to a S/W problem. In addition to these focusing missions, an Indian satellite, **ASTROSAT**, with non-focusing hard X–ray instrumentation, has been launched, which can be considered as a *RXTE* follow-up. In addition to these missions, it merits to mention the very small (3.8 kg) GAmma–ray burst Polarimeter (**GAP**) devoted to measure the polarization of bright GRBs in the 50–300 keV band. GAP has been launched in 2010 aboard the Japanese solar–power sail demonstrator **IKAROS** (Yonetoku et al. 2011b), with some significant results already obtained (Yonetoku et al. 2011a, 2012).

In this epoch there are very few balloon experiments. We mention here the **PoGOLite Pathfinder** experiment devoted to test the performance of the **PoGOlite** polarimeter (Chauvin et al. 2016).

3.5.1 Satellite missions

We discuss *NuSTAR* and the Indian mission *ASTROSAT*.

– **NuSTAR**
The NUclear Spectroscopic Telescope ARray (*NuSTAR*) (Harrison et al. 2013) was launched on June 13, 2012 by a Pegasus-XL rocket. It is the first satellite mission that makes use of focusing telescopes to image the sky in the 3-79 keV energy range. Based, in large part, on the technologies developed for the HEFT balloon experiment (see above), it is still operational.
It consists of 2 co-aligned grazing incidence hard X-ray telescopes focusing onto position sensitive detectors, with 18 arcseconds FWHM angular resolution. Their focal length is 10.14 m obtained with an extendable mast. Each optic module contains 133 nested multilayer-coated grazing incidence shells in a conical approximation to a Wolter-I geometry. Each shell is coated with depth-graded multilayer structures which increase the grazing angle with a significant reflectivity. The inner 89 shells are coated with depth-graded Pt/C multilayers that reflect efficiently below the Pt K–absorption edge at 78.4 keV. The outer 44 shells are coated with depth-graded W/Si

multilayers that reflect efficiently below the W K–absorption edge at 69.5 keV. Focal plane detectors, surrounded by a CsI anti-coincidence shield, are made of a 2×2 array of CZT counters. The best time resolution is 2μs.

With NuSTAR, for the first time, most classes of Galactic and extragalactic sources become visible in hard X–rays. Among the Galactic sources, we mention the first detection of high-energy X-ray emission from the Galactic center non-thermal filament G359.89−0.08 (Sgr A-E) (Zhang et al. 2014a), the first hard X–ray image of the inner 5'×5' (12 pc×12 pc) of the Galaxy with an angular resolution of 18" (Perez et al. 2015), the first detection of hard X–ray emission from the Arches star cluster (11 arcmin from Sgr A*) (Krivonos et al. 2014), the observation of the first energy-dependent hard phase lag (up to 4 s) in the pulse profile of the transient Be/X-ray binary pulsar ($P \sim 12.29$ s) GS 0834−430, never reported before from a high–mass X–ray binary pulsar (Miyasaka et al. 2013), the observation at soft and hard X–rays of magnetar sources, e.g. 1E 1841−045 (An et al. 2013) confirming the non-thermal component at high-energies but also the need to extend the energy band of the focusing telescopes to higher energies in order to fully test magnetar models (e.g. Beloborodov 2013), the discovery of the transient magnetar SGR J1745−29 with a hard spectral tail located at the Galactic centre (Mori et al. 2013), the first hard X–ray image of the Pulsar Wind Nebula (PWN) MSH 15−52 and its total spectrum up to 20 keV (An et al. 2014), the first sensitive hard X–ray spectrum of a neutron star transient in quiescence, Cen X–4, finding, unexpectedly, that the hard X–ray component is consistent with a thermal bremsstrahlung model with $kT_e = 18$ keV (Chakrabarty et al. 2014), the first hard X-ray detection of transitional pulsars, like PSR J1023+0038, which switch between an accretion–powered state (LMXB) and a rotation–powered state (radio ms-pulsar) (Li et al. 2014).

Concerning extragalactic sources, we mention the first detection of a SN (SN 2010jl) outside the Local Group in the hard X-ray band (Ofek et al. 2014), the first detection of a young extragalactic stripped-envelope SN (2014C) out to 40 keV (Margutti et al. 2016), the hard X–ray spectral detection of Ultraluminous X–ray sources, e.g. ULX 5 in the Circinus galaxy (Walton et al. 2013) and ULX 2 in M82 from which a 1.37 s pulsation was discovered, implying a magnetized neutron star as emitting source (Bachetti et al. 2014), the capability to study extremely active supermassive black holes located at very high redshift, like the blazar B2 1023+25 ($z = 5.3$) (Sbarrato et al. 2013), the best signal-to-noise ratio obtained to date from active galactic nuclei over the 3-79 keV band, as in the case of the Seyfert 1 galaxy IC 4329A, whose high–energy cutoff ($E_{cut} = 178^{+74}_{-40}$ keV, Brenneman et al. 2014)) could be determined, the inference of a maximally rotating supermassive black hole (NGC 4051) from the spectral property of hard X–ray radiation (Risaliti 2014).

Also deep extragalactic surveys have been performed at hard X–ray energies to characterize the source population that contributes to the high–energy CXB (e.g., Alexander et al. 2013; Civano et al. 2015).

Another very important result is the detection of the hard X–ray afterglow (up to 79 keV) (see Fig. 19) from a very bright GRB (130427A) (Kouveliotou et al. 2013), after the first detection of a X–ray afterglow (from GRB 990123) obtained with the *BeppoSAX* PDS instrument (Maiorano et al. 2005). These hard X–ray afterglow observations are crucial to establish the emission mechanism of the GRB afterglow and characterize the circumburst environment. They should be extended to higher energies.

Several results also concern CRSFs in X–ray pulsars. Some of them concern the discovery of further properties of the CRSFs already known, e.g. Her X–1 (Fürst et al. 2013) and Vela X–1 (Fürst et al. 2014b). Another significant result concerns the confirmation of a line feature at

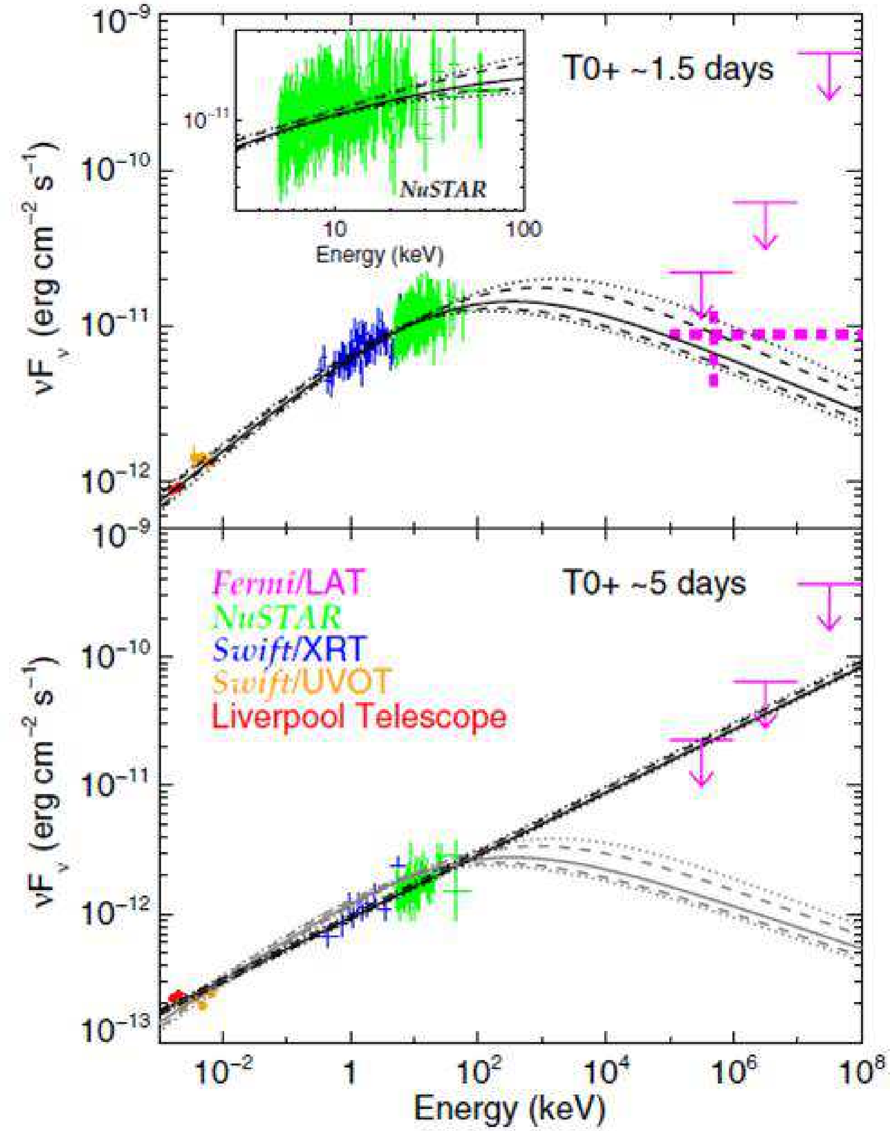

Fig. 19 Afterglow spectrum of GRB 130427A measured up to 79 keV with NuSTAR, after 1.5 and 5 days after the event. The extension of the measurements at high energies is crucial to establish the emission mechanism of the afterglow radiation. Reprinted from Kouveliotou et al. (2013).

78 keV from the high-mass X-ray binary GRO J1008−57 (Bellm et al. 2014). Also new CRSFs have been discovered, like a variable line at 12.5 keV from the transient Be–neutron star binary KS 1947+300 (Fürst et al. 2014a), and a CRSF at 31.3 keV from the ROSAT X–ray pulsar RX J05205−6932 during a high luminosity (3.6×10^{38} erg s^{-1}) outburst (Tendulkar et al. 2014). Important is the first measurement of a cyclotron line at 17 keV from a SFXT (IGR J17544−2619),

from which the surface magnetic field could be derived ($B = (1.45 \pm 0.03) \times 10^{12}(1+z)$ G, z being the gravitational redshift), demonstrating the NS nature of these sources (Bhalerao et al. 2015).

– **ASTROSAT**
  ASTROSAT is the first indian satellite devoted to multiwavelength observations from space. It was launched by the Indian launch vehicle PSLV from the Satish Dhawan Space Centre, Sriharikota, on 2015 September 28.
  The five instruments on board (Singh et al. 2014) cover the visible, near UV, far UV, soft X-ray band and hard X-ray (3-80 and 10-150 keV) band. In the 3–80 keV passband, *ASTROSAT* makes use of a cluster of 3 co-aligned identical Large Area X-ray Proportional Counters (**LAX-PCs**), each with a multi-wire-multi-layer configuration and a FOV, obtained through mechanical collimators, of $1° \times 1°$ FWHM (Yadav et al. 2016b).
  In the 10–150 keV passband, *ASTROSAT* uses an imaging telescope (**CZTI**) with an angular resolution of 8 arcmin. It consists of a pixellated CZT detector array surmounted by a two–dimensional coded mask. CZTI is expected to provide measurements of the X-ray polarization level of bright X-ray sources in the energy range of 100-300 keV (Vadawale et al. 2015) to constrain, with an exposure time of 100 ks, any intrinsic polarization greater than ∼40% (>500 mCrab) at 3σ confidence level.
  At the time of this paper, in addition to GCNs on the detection of GRBs (e.g., Vadawale et al. 2016), scientific results are being published. We wish to mention the polarization study of the first GRB (151006A) observed with *ASTROSAT* (Rao et al. 2016b), and the observation of the micro–quasar GRS 1915+105, with the study of the its power spectrum with energy and 2–8 Hz QPO (Yadav et al. 2016a). A review of the first results obtained with *ASTROSAT* is given by Rao et al. (2016a).

4 Achievements, open problems and future prospects

From the review of the experiments discussed above, it appears clear that hard X–ray astronomy has reached a very advanced stage of development. Since the beginning (see Section 2), its key role has been the determination of the emission mechanisms at work in X–ray celestial sources. In the 1970s/1980s, this was possible only for the brightest sources. With the increase of the experiment useful or effective area (see Fig. 20) and thus of sensitivity (see Fig. 21), the emission mechanisms of weaker sources could be investigated. Thanks to satellites, like *BeppoSAX*, *Rossi XTE* and *INTEGRAL*, we have seen that, in order to investigate the emission mechanisms at play in X–ray sources, the measurement of broad–band spectra from soft X–rays to hard X–rays/soft gamma–rays, is crucial. This broad–band study should be now extended to several hundreds of sources, Galactic and extragalactic, of different classes, that are known to be hard X–ray emitters also on the basis of the INTEGRAL/IBIS and Swift/BAT sky surveys discussed above. To get broad band spectra up to hard X–ray/soft gamma–ray energies for the weakest sources, direct–viewing telescopes, in spite of their very exciting results obtained so far, are inadequate owing to their limited sensitivity (see Fig. 21). The solution is the use of broad band X–ray focusing telescopes. At low X–ray energies (≤10 keV), it is already many years that focusing is a mature technology, while at hard X–ray energies up to about 80 keV the technology has become mature only recenty, as brilliantly demonstrated by the *NuSTAR* mission. However, even the *NuSTAR* results have demonstrated that an extension of the focusing to higher energies and a better sensitivity in the upper part of the *NuSTAR* telescope passband (>30-40 keV) are a must.

Laue lenses offer a viable solution to the implementation of a focusing telescope up to 600 keV and beyond (see, e.g., Frontera et al. 2013). The Laue lens development is in an advanced stage and Laue lenses are expected to achieve sensitivities 2–3 orders of magnitude better than the *INTEGRAL* sensitivity at the same energies and a much better angular resolution ($\sim$ 20 arcsec) (Virgilli et al. 2017).

In the mean time, a Chinese mission, the Hard X-ray Modulation Telescope (**HXMT**) (Li 2007; Zhang et al. 2014b), just launched (June 15, 2017) and renamed **Insight**, could do an important job for broad–band studies. Indeed it includes a low–energy (**LE**; 1–15 keV), a medium–energy (**ME**; 5–30 keV) and a high–energy (**HE**; 20–250 keV) instrument. The *HE* telescope consists of 18 NaI(Tl)/CsI(Na) phoswich crystals, with a design similar to that of the BeppoSAX/PDS, but with a much larger total geometric area (about 5000 cm^2). Thanks to the collimator configuration, **HE** is also capable to perform, with an angular resolution of about 5 arcmin, imaging of the sky region in its FOV (5.7° × 5.7° FWHM). The telescope is expected to achieve a continuum sensitivity of about 3×10^{-7} ph cm^{-2} s^{-1} keV^{-1} at 100 keV (3σ, 100 ks). Main goals of HXMT include a sensitive monitoring of the Galaxy plane and broad band (1–250 keV) pointed observations of peculiar objects.

Almost contemporarily, a Gamma-Ray Burst polarimeter **POLAR** was launched on September 15, 2016 aboard the Chinese space laboratory Tiangong-2 (TG-2), and is still in the Science Verification Phase, for polarization measurements of the GRB prompt emission in the 50–500 keV band (Kole et al. 2016).

Also devoted to GRB studies in a broad passband is the **SVOM** Sino–French mission, whose launch is foreseen in 2021. It includes a coded-mask telescope operating in the 4-150 keV energy range for real-time GRB detection and prompt localization, and a non-imaging gamma-ray monitor for GRB spectroscopy from 15 keV to 5 MeV (Wei et al. 2016).

No other hard X–ray instruments are at this time approved for satellite missions. We expect that, once the technological developments are accomplished, future missions with broad band optics, hopefully inclusive of Laue lenses, can eventually perform not only deep studies of the many hard X–ray sources discovered with INTEGRAL and Swift/BAT and of those expected to be discovered in the next years with HXMT, but also solve fundamental issues still open in astrophysics.

Among them, we wish to mention the origin of the 511 keV annihilation line from the Galactic Center region. We have seen that the presence of this line, initially discovered with balloon experiments (Leventhal et al. 1978), is now well established. The monitoring of the line with balloon experiments found it variable with upper limits to its intensity (e.g., Leventhal et al. 1986) in the same years in which the *SMM* Gamma–Ray Spectrometer with a broader FOV detected it (Share et al. 1990). These seemingly contradictory results opened the possibility that this line was partly due to a diffuse emission, and partly to point–like sources (Lingenfelter and Ramaty 1989). INTEGRAL measured the space distribution of the emission, but, due to the still low angular resolution (12 arcmin), has left the origin of this radiation unsolved, whether it is the result of a superposition of point–like sources, or it is intrinsically diffuse or a combination of both types. Only a focusing telescope with much higher sensitivity than INTEGRAL and with a much better angular resolution could settle the issue, and establish the nature of the emission. An exciting possibility is that this line is due to dark matter annihilation.

Related to the previous issue, it is of great relevance to confirm the result found with INTEGRAL in the case of V404 Cygni (Siegert et al. 2016), and, previously, with SIGMA aboard GRANAT in

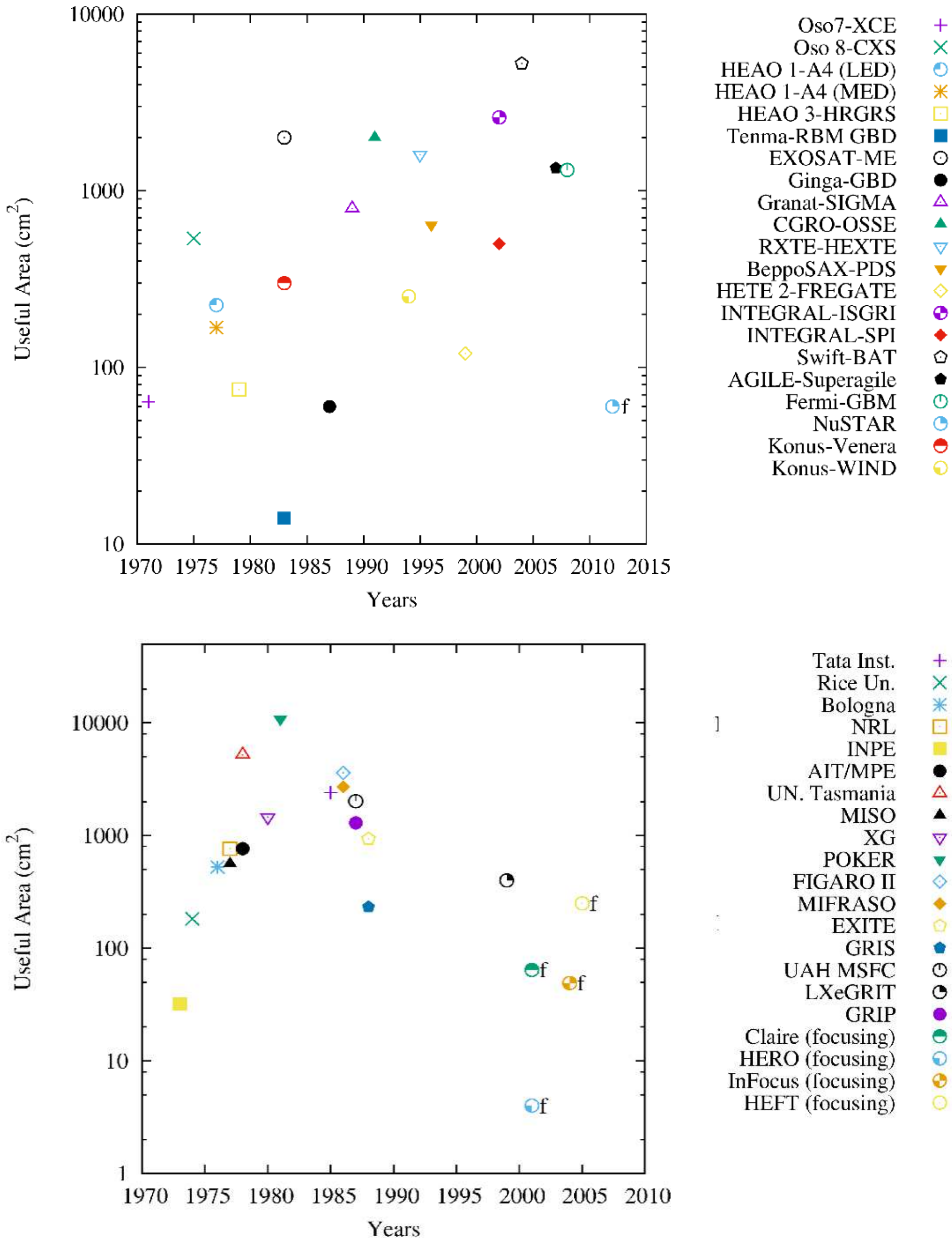

Fig. 20 Trend with time of the useful area, defined as the geometrical area through the collimator or coded mask, of the hard X–ray non-focusing instruments. In the case of focusing instruments (marked with "f"), it is shown the trend with time of the effective area. *Top panel*: Satellite instruments. Data are taken from Table 1. *Bottom panel*: balloon instruments. Data are taken from Table 2.

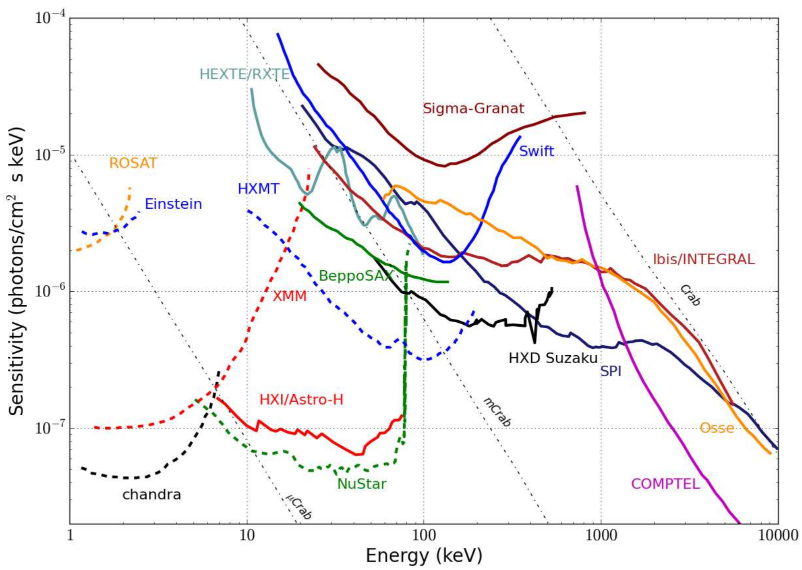

Fig. 21 Three sigma sensitivity, for an exposure time $T = 10^5$ s and a bandwidth $\Delta E = E/2$, of the most relevant missions in the hard X–ray/soft gamma–ray band. Adapted from Virgilli et al. (2017).

the case of Nova Muscae (Goldwurm et al. 1992), that the 511 keV positron annihilation line has origin in microquasars. This can be done by studying a significant sample of microquasars with much higher sensitivity.

Another still open issue is the systematic study of explosive events, like thermonuclear or core–collapse Supernovae, through the detection of nuclear lines produced in the explosion, in particular the 158 keV line from ^{56}Ni, and the 67.9 and 78.4 keV lines from ^{44}Ti.

Another relevant open issue is the determination of the still mysterious shape of the high–energy spectra of anomalous X–ray pulsars and SGRs. We have seen that a hard tail from these sources has been determined with INTEGRAL plus RXTE up to 100 keV. However, in order to establish its origin (e.g., Beloborodov 2013), the detection should be extended beyond this energy, where now only upper limits can be given (Kuiper et al. 2006, 2008; Götz et al. 2006).

In spite of their importance for establishing the physics and their contribution to the high–energy Cosmic X–ray Background, the high–energy spectra of AGNs are still poorly known beyond 100 keV. This knowledge is important to determine their cutoff energies and, in the case of Blazars, the determination of their spectra in the critical band around 400 keV where the spectra are still undetected.

As we have seen, GRBs have been discovered in the hard X–ray band. This band, extended to the MeV region from one side, and to low energy X–rays from the other side, is crucial not only to investigate the still debated physics of the GRB prompt emission but also its afterglow. The few detections of hard X–ray afterglow emission available so far (one with BeppSAX (Maiorano et al. 2005) another with NuSTAR (Kouveliotou et al. 2013)) have shown the importance of the high–energy spectra in order to establish the afterglow emission mechanisms. Unfortunately, these observations are very rare due to the limitations of the instruments and the parallel need of prompt follow up of promptly localized GRBs. Also in this case, much more sensitive hard X–ray/soft gamma–ray instruments are requested for the study of the GRB afterglow.

Another important issue is the polarization level of the high–energy emission from different classes of sources. Thus far we have very few polarization results: those obtained with the Gamma–Ray Burst Polarimeter (GAP) aboard the solar-power sail demonstrator IKAROS (Yonetoku et al. 2011a, 2012), and those obtained with INTEGRAL from Crab (Dean et al. 2008), Cygnus X–1 (Jourdain et al. 2012) and some GRBs (Götz et al. 2009, 2013, 2014) we have discussed above. These results have shown the importance of the polarization measurements for establishing the emission mechanisms. A much better sensitivity is requested to extend this search to different classes of sources, taking into account that the polarization properties can change with the time scale of the X–ray source variability and destroy the polarization level if the observation time requested to achieve the needed sensitivity is longer.

We expect that only focusing telescopes extending the band at least up to 600 keV can solve the above and many other open issues. For the first time a new window will be open beyond 100 keV ushering in a large discovery space and making a great breakthrough in the knowledge of the high–energy Universe.

In addition to the studies of peculiar objects or sky regions, also a sensitive soft gamma–ray monitoring of wide regions of the sky is important in a band, beyond 100 keV, yet scarcely explored. This could allow, among others, to discover new persistent and transient gamma–ray sources, inclusive of supernovae explosions, to study GRBs and other transient phenomena, like Tidal Disruption Events, Soft Gamma–Ray Repeaters, electromagnetic counterparts of Gravitational Wave Events, possible high–energy emission associated to Fast Radio Bursts (DeLaunay et al. 2016), to study their polarization properties, and to discover new diffuse line emission of nuclear origin. To do that, a new generation of telescopes is required with a significantly better sensitivity than that of the INTEGRAL mission at the same energies. A possibility that could have been offered by the wide field ($90^\circ \times 70^\circ$) High–Energy Telescope (5–600 keV) proposed for the EXIST mission (e.g., Grindlay et al. 2010), unfortunately not approved by NASA. Another possibility is the Pair And Compton Telescope (PACT; 100 keV–100 MeV) (Laurent et al. 2014), with a wide FOV (>3 sr), but with a still poorer angular resolution (of the order of 1 deg below 10 MeV). The development status of this instrument is advanced.

The combination of both wide field hard X–ray/soft gamma–ray instruments and broad–band narrow field telescopes up to hard X–rays/soft gamma–rays on board of one or more satellites could be a winning strategy of the next step of the hard X–ray/soft gamma–ray astronomy for an unprecedented study of the high–energy Universe.

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Table 3: Acronyms

AGILE	Astrorivelatore Gamma a Immagini LEggero
AGN	Active Galactic Nuclei
AIT	Astronomisches Institut der Universitat Tubingen
ART-P	Astrophysical Roentgen Telescope
ART-S	Astrophysical Roentgen Telescope-Spectrometer
AS	Alice Springs
ASM	All-Sky X-ray Monitor
AXP	Anomalous X-ray Pulsar
BAT	Burst Alert Telescope
BATSE	Burst And Transient Source Experiment
BGO	Bismuth Germanate
BHC	Black Hole Candidate
BM	Burst Mode
C	mechanical Collimator
CAL	CALibration system
CEA	Commissariat l'nergie atomique et aux nergies alternatives
CESR	Centre d'Etude Spatiale des Rayonnements
CGRO	Compton Gamma-Ray Observatory
CM	Coded Mask
COMPTEL	COMPton TELescope
CRSF	Cyclotron Resonance Scattering Feature
CT	Compton Telescope
CXB	Cosmic X-ray Background
CXRS	Cosmic X-Ray Spectroscopy
CZTI	Cadmium Zinc Telluride Imager
EXIST	Energetic X-ray Imaging Survey Telescope
EXITE	Energetic X-ray Imaging Telescope Experiment
EXOSAT	European X-ray Observatory SATellite
FO	Focusing Optics
FCFOV	Fully Coded Field of View
FIGARO	French Italian GAmma Ray Observatory
FOV	Field Of View
FREGATE	FREnch GAmma-ray TElescope
FWHM	Full Width at Half Maximum
GBD	Gamma-ray Burst Detector
GC	Galactic Center
GeD	Germanium Detector
GLAST	Gamma-ray LArge Space Telescope
GRB	Gamma-Ray Burst
GRBM	Gamma-Ray Burst Monitor
GRIS	Gamma-Ray Imaging Spectrometer
GSPC	Gas Scintillation Proportional Counter
HDX	Hard X-ray Detector
HEAO	High-Energy Astronomy Observatory

HED	High-Energy Detector
HECX	High-Energy Celestial X-rays
HEFT	High-Energy Focusing Telescope
HERO	High-Energy Replicated Optics
HET	High-Energy Telescope
HETE	High-Energy Transient Explorer
HEXE	High-Energy EXperiment
HEXTE	High-Energy X-ray Timing Experiment
HMXRB	High-Mass X-Ray Binary
HPD	Half Power Diameter
HPGSPC	High Pressure Gas Scintillation Proportional Counter
HRGRS	High Resolution Gamma-Ray Spectrometer
HWHM	Half Width at Half Maximum
HXD	Hard X-ray Detector
HXI	Hard X-ray Imager
HXMT	Hard X-ray Modulation Telescope
HXT	Hard X-ray Telescope
IBIS	Imager on-Board the INTEGRAL Satellite
InFOCνS	International Focusing Optics Collaboration for muCrab Sensitivity
INPE	National Institute for Space Research
INTEGRAL	INTErnational Gamma-Ray Astrophysical Laboratory
ISGRI	INTEGRAL Soft Gamma-Ray Imager
ISAS	Institute of Space and Aeronautical Science
LAC	Large Area proportional Counter
LAD	Large Area Detector
LAT	Large Area Telescope
LAXPCs	Large Area X-ray Proportional Counter
LED	Low Energy Detectors
LEGR HXSS	Low-Energy Gamma-Ray and Hard X-ray Sky Survey
LL	Laue Lenses
LMXB	Low Mass X-ray Binary
LS	Liquid Scintillator
LXeGRIT	Liquid Xenon Gamma-Ray Imaging Telescope
ME	Medium Energy
MED	Medium Energy Detector
MIFRASO	MIlano FRAscati SOuthampton
MISO	MIlan SOuthampton
MPE	Max Planck Institute for Extraterrestrial Physics
MPI	Max Planck Institute
MSFC	NASA Marshall Space Flight Center
MSP	MilliSecond Pulsar
MWPC	Multi-Wire Proportional Counter
NA	Not Applicable
nd	no data
NM	Normal Mode
NRL	Naval Research Laboratory

OSO	Orbiting Solar Observatory
OSSE	Oriented Scintillation Spectrometer Experiment
PC	Proportional Counter
PCA	Proportional Counter Array
PCFOV	Partially Coded Field Of View
PD	Phoswich Detector
PDS	BeppoSAX Phoswich Detection System
PS	Plastic Scintillator
PMT	Photo Multiplier Tube
PSD	Position Sensitive Detector
PWN	Pulsar Wind Nebula
QPOs	Quasi Periodic Oscillation
RBM/GBD	Radiation Belt Monitor-Gamma-ray Burst Detector
RC	Rocking Collimator
RMC	Rotation Modulation Collimator
RXTE	Rossi X-ray Timing Explorer
SAA	South Atlantic Anomaly
SAS	Small Astronomical Satellite
SAX	Satellite per Astronomia X
SBC	Sanriku Balloon Center
SCD	Slat Collimator Detector
SD	Scintillation crystal Detector
SFXT	Supergiant Fast X-Ray Transient
SGD	Soft Gamma-ray Detector
SGR	Soft Gamma-ray Repeater
SSD	Silicon Detector
SXC	Soft X-ray Camera
SXI	Soft X-ray Imager
SXS	Soft X-ray Spectrometer
TCD	Tube Collimated Detector
TDF	Tidal Disruption Flare
TGF	Terrestrial Gamma-ray Flash
TIFR	Tata Institute of Fundamental Research
UAH	University of Alabama in Huntsville
UCR	University of California Riverside
UCSD	University of California San Diego
ULX	Ultra Luminous X-ray Source
URA	Uniformly Randomized
USC	Uchinoura Space Center
UVOT	UV and Optical Telescope
XCE	X-ray Cosmic Experiment
XG	X-Grande
XIS	X-ray Imaging Spectrometer
XRF	X-Ray Flash
XRS	X-Ray Spectrometer
XRT	focusing X-Ray Telescope

WAM	Wide-band All-sky Monitor
WATCH	Wide Angle Telescope for Cosmic Hard X-rays
WFC	Wide Field Camera

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