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Memorie della

BeppoSAX: history and legacy

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Abstract. Launched on April 1996, operational for six years, BeppoSAX has opened a new view on the X-ray universe, with its broad-band and wide angle instruments associated with flexible ground segment operations. In this paper we recall some of the history behind the development of the project, summarize some of its scientific achievements and comment on its heritage.

1. Introduction

The early development of Space science in Italy after the second world war was essentially driven by the joint demands of high energy (astro)physics science, represented by Edoardo Amaldi on one side and the rocketry field promoted by Luigi Broglio on the other. They together led to the establishment of an Italian space programme in 1959 through CRS (Consiglio Ricerche Spaziali), including as science advisors G. Puppi in Bologna and Beppo Occhialini in Milan. In those years Italy developed an independent capability in space facilities, with the establishment of the San Marco base in Malindi, that served several national and international satellites in the 70's including the Italian San Marco satellites series (for the study of atmosphere), the NASA X-ray satellites SAS-1 (Small Astronomy Satellite), renamed "Uhuru" ("freedom" in Swahili), SAS-2, and SAS-3, or the british Ariel V.

An important evolution, for which Beppo Occhialini was one of the key player, was the action to shift the responsibility for science research in space to a body independent of military interests. This was the National Space Plan under the umbrella of CNR (National Council of Research), that eventually evolved in an independent space agency, ASI, in 1988.

The development of space science was mostly driven by scientist working on Cosmic Rays, in particular G. Puppi and E. Amaldi who, after the CERN experience, strongly advocated for a similar European body in the field of space research. They played a key role in the foundation of the first European bodies for Space, the European Space Research Organization (ESRO) and European Launcher Development Organisation (ELDO), eventually merged to form ESA in 1975. A crucial role in this last step was played by G. Puppi, who was the chair of the ESRO council in the years preceding the establishment of ESA.

Beppo Occhialini, a student of Bruno Rossi in 1927, was already famous for his seminal contribution to the discovery of the e^+ with Blackett and of the π meson with Powell, when he moved from Genua to Milan in 1952, where he founded a space research group, with a programme based first on stratospheric bal-

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loons. His interest in promoting space research in Italy was consolidated after a sabbatical semester at MIT discussing with Bruno Rossi and his collaborators on the future of space research. In addition to his leading role in promoting national activities, Occhialini was a key person in ESRO, and the first chair of the COS (Cosmic Ray Group). This group planned the first European gamma-ray experiment COS-B, launched in 1975. Interestingly the other mission designed by the group, COS-A, was devoted to X-ray Astronomy. It was then re-elaborated as HELOS (Highly Eccentric Lunar Occultation Satellite) by Connie Dilworth in Milan and J.A.M. Bleeker in Utrecht, finally evolving into the EXOSAT satellite, launched in 1983 by ESA.

One of first students of Beppo, when he had just returned to Italy, in Genua, in 1949, was Livio Scarsi. Livio was immediately engaged in the Cosmic Ray field and then, after the advise of Beppo, moved to MIT in 1957, joining Bruno Rossi and John Linsley in the experiment on giant Extensive Air Shower Array at Volcano Ranch, near Albuquerque.

In the early 60's Livio took part in extensive discussions at MIT with Beppo Occhialini and Bruno Rossi on space research, before coming back to Milan in 1961. After a brief period at the University of Rome La Sapienza from 1981 to 1983 as Chair of Space Physics (fundamental for the author of this paper, who was captured in this field by the enthusiasm and fascination of Livio), he was in Palermo as director of the CNR institute on Cosmic Physics. In those years, as chairman of the BeppoSAX steering committee, he guided the programme to a successful end.

The role of Bruno Rossi was significant also for another branch of space Astrophysics in Italy. After his advice Giuseppe Vaiana, who had moved to MIT in the early 60's, took up the X-ray solar astronomy project, building instruments aboard rockets, OSO satellites and the SKylab. Coming back in Palermo in 1975, he created the Italian school of Stellar X-ray Astronomy. In Bologna G. Puppi was well renowned for his contributions to the field of Cosmic Rays. Engaged by the fast developments in X and gamma-ray astronomy that were taking place in the late 50's, he promoted the foundation of a research group focussed on this topic under the guidance of D. Brini. The quality of the h/w development carried out in the laboratory was well recognized at international level, leading to the first Italian experiment aboard a NASA mission, namely OSO-6, launched in 1969.

Another important step in development of the high energy space Astrophysics in Italy is linked to the return of Livio Gratton back from Argentina in 1960. First in Bologna, called by Puppi, Gratton then moved to Rome called by Amaldi, where he founded in Frascati the Laboratory for Space Astrophysics. The laboratory encompassed various research themes but, as the name says, the main mission was space astronomy. Gratton appreciated the technological potential of X-ray astronomy and promoted the field engaging his laboratory in a series of experiments, some in collaboration with MIT, that included rocket campaigns with scientific payload designed and build in Frascati. The structure of the space-oriented astrophysical laboratories (later to become institutes) was formalized in the late 60's for Milan, Bologna and Frascati and in the early 80's for Palermo following the recommendation of the Physics council of CNR chaired by G. Puppi in the first instance and then by G. Setti. This action provided a strong backbone for the future development of the field, and it is not a case that those institutes were the main constituents of the BeppoSAX project.

2. BeppoSAX

In 1981 the Italian National Space Plan (PSN) managed by CNR and led by Luciano Guerriero issued an Announcement of Opportunity for a national astronomical mission. This key step in the development of space science in Italy was needed to cope with a rapidly growing field with strong demand of investments by the scientific community and national space industries, investments that could not fit in the somewhat limited budget of the ESA obligatory program (Setti 2005). The AO guidelines thus required top-level science, a substantial involvement of the na-

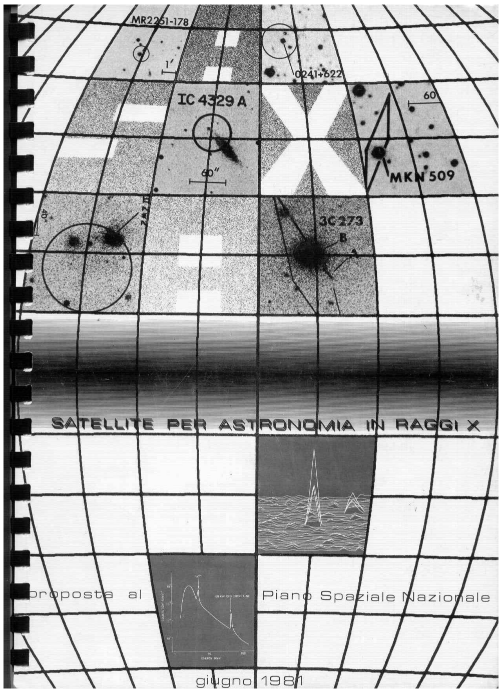

Fig. 1. Cover of the SAX proposal submitted in 1981 to the National Space Plan

tional scientific community and space industry and an international participation. Three proposals were submitted, including one on IR observations, but only two were carried on for an assessment study. OOXA, acronym for Orbiting Observatory for X-Ray Astronomy) and SAX, Satellite per Astronomia X. SAX was proposed (see Fig.1) by a consortium of institutes, including the CNR institutes in Frascati (IAS), in Bologna (ITeSRE), in Milan (IFCTR) and in Palermo, (IFCAI), Universities of Rome and Palermo, and two international partners: SRON and SSD/ESA. MPE was later involved for telescope calibrations. The multi-instrument design was the key approach to cope with the main scientific driver of the mission (broad band and wide sky coverage). It also allowed an involvement of a large consortium of instititues in the design, development and realization of the mission and its scientific instruments. An equatorial orbit was selected, to take full advantage of low particle and low modulation of the background and to use the Italian ground station in Malindi in Kenya. The launch profile was based on Shuttle deployment in low orbit with injection at 600 km by an experimental Italian module (IRIS).

After an assessment phase carried out by Aeritalia (now Thales Alenia Space) in 1982 SAX was selected by PSN following the advice of an Advisory Panel composed by E. Amaldi, G. Occhialini, B. Rossi, G. Setti and L. Woltjer.

Extended phase A study was carried out by Aeritalia & Laben in 1984-1986. In this phase the payload was upgraded with the inclusion of Concentrators Spectrometers with electroformed X-ray mirrors. Phase B was due to start in 1986. However, in Jan.86, the Challenger disaster put the SAX program in hold for almost two years. In mid 87 SAX was reoriented for a launch with Atlas-Centaur, and a new phase B started in 1988. The delay accumulated by the project, following also the re-organization of space activities under the newly established space agency ASI in 1988, triggered in the following years harsh discussions, involving also unjustified doubts on the scientific merit of the mission.

Following this situation, in 1993 The Minister for Universities and Scientific and Technological Research, U. Colombo, requested an independent advise on the continuation of the program to the European Space Science Committe of the European Science Foundation. On Nov.11 the SAX program was presented by L. Scarsi, G.C. Perola and the author to the ESSC/ESF board, chaired by H. Schnopper. The board recommendation was issued on Nov.30, reporting that: *Because of the short notice the panel could not thoroughly examine the project, therefore managerial and financial aspects were not developed. However, based on the scientific arguments put forward by the SAX representatives, the panel of experts recommends that ASI should continue to support SAX.* In particular the panel recognized *..the unique scientific potential of SAX. The complement of the four bore-sighted X-ray spectromenters constitutes an unprecedented combination of large badwidth (3 orders of magnitude) and spectral resolving power. This wide-band capability, linked to the source de-*

tection capabilities of the WFC, provides an unprecedented potential for dynamical studies of transient phenomena in the X-ray sky. This is in fact the main SAX asset, that has then become famous for the discoveries in the field of GRB, and that has delivered important results in several other fields, including AGN, compact galactic sources, clusters, SNRs, stars, etc., as reported extensively in literature. In parallel G. Puppi, who had been nominated special administrator of ASI in 1993, charged G. Setti with a full review on the status of the SAX programme which took place at ASI HQ on Oct.25-26. In a detailed report (in Italian) sent to Puppi on Nov.16, the continuation of the SAX mission was strongly recommended, based on science quality and advanced schedule, together with several suggestions in order to speed up and control the completion of the project.

It is worth pointing out that most of the delays in the programme were due to decision-making process, and the most significant was that related to the Shuttle problem. When one compares SAX with other X-ray satellites initially designed to be deployed by Space Shuttle, the delays are very similar. Predicted launch dates in the early 80's were in between 1990 (Zombeck 1982) and 1992 (Giacconi 1985)for AXAF (launched in 1999), 1990 (Bradt et al. 1985) for XTE (launched in 1995) and end of 1989 (Scarsi 1985) for SAX (launched in 1996).

3. Technical challenges before launch

The development of the project was interspersed with technical problems, all successfully solved. The most concerning problems were the following.

The first model of the HPGSPC instrument showed discharging due to the very high voltage required by the instrument. This problem was eventually solved by redesigning the part of the detector where the electric field was too high.

The WFC units showed occasional sparking. The problem was spotted in the wiring and solved by rewiring the anode frames.

The effect of interaction of ion-plasma with the MECS and LECS was deeply studied and tested in a plasma chamber facility. The concern was that the positive ions from plasma present in the low earth orbit environment would have been accelerated by the negative high-voltage windows of the LECS & MECS detectors (10-20 kV), increasing the background by the production of bremsstrahlung X-rays. This effect was also considered in the GIS instrument aboard ASCA. The solution implemented was an electrostatic grid below the X-ray optics, with the further addition of plasma protective windows (based on polymide) just above the MECS and LECS detectors. Eventually the in-orbit background was consistent with the predictions.

Just 3 months before launch, when all the payload was integrated on the satellite at the site launch, system tests showed that the calibration source of the HPGSPC was producing a very high background in the Gamma-Ray Burst Monitor (GRBM). This problem was solved with the addition of a further shield around the radioactive source. It is interesting to note that, without this operation, GRB observations would have been severely hampered.

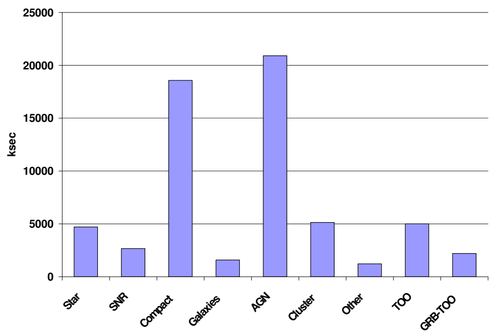

Fig. 2. Total observing time of NFI for different classes of sources

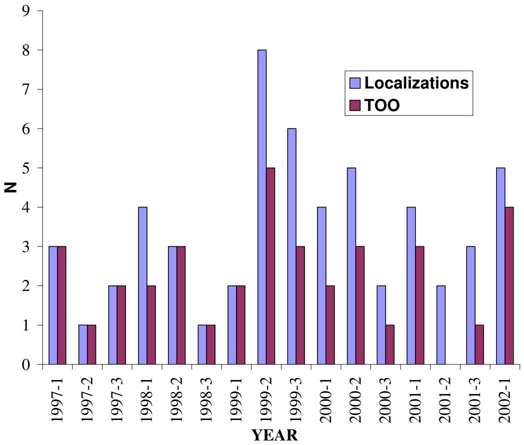

Fig. 3. Number of real time localizations and fast TOO of GRBs every four months vs year

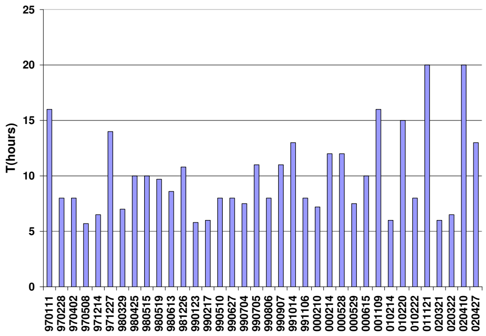

Fig. 4. Fast follow-up observations of GRB localized by BeppoSAX: beginning of the observation in hours after the GRB

4. Launch and operations

SAX was launched from Cape Canaveral on April 30, 1996 4:31 GMT and injected at the required 600 km, 3.9deg inclination orbit. After launch it was named BeppoSAX, in honour of Giuseppe "Beppo" Occhialini by the Italian Minister of Research and Education Salvini. After successfully completing the commissioning phase, full scientific operation started on July 1996.

BeppoSAX was switched-off on April 30, 2002 (the last observation was a GRB Target of Opportunity), mostly because the atmospheric drag was starting to affect substantially operations. It re-entered in atmosphere on 29 April 2003, 22:06 UTC, disintegrating in the midst of the Pacific Ocean (in fact, April 30 Italian time: this was a curious coincidence, since there was no way to control the re-entry date).

The scientific payload comprised a total of 9 instruments (four focal plane GSPC's, 2 WFCS's, HPGSPC, PDS, plus the dedicated electronics to use the lateral shields of the PDS as GRBM) and 4 X-ray optics (a detailed description of the mission and its instruments can be found elsewhere Piro et al. 1995a; Boella et al. 1997a; Parmar et al. 1997; Boella et al. 1997b; Manzo et al. 1997; Frontera et al. 1997; Jager et al. 1997; Costa et al. 1998).

The performances of the mission were consistent and, in several cases, superior, to prelaunch requirements. Few problems, described below, were solved and did not affect significantly the scientific return of the mission. Merit of this behavior goes to the commitment of several people, from those, quoted above, which designed and implemented it, to those that operated it after launch. It is impossible to acknowledge them all. Nonetheless I would like to recall the driving force provided by Livio Scarsi, Giuliano Boella, Cesare Perola and Johan Bleeker in steering safely the program throughout phases often very challenging, and the fundamental role of Chris Butler as Mission Director.

Problems were limited to one of the MECS, that in May 97 was switched off due to a failure in the high voltage supply, and to sun light contamination in the LECS, that was solved by operating the detector only during the dark part of the orbit. The so called gyro problem was the most important technical challenge faced during the mission. The system was designed with a high level of redundancy, considering that gyro problems affected other astronomical missions of the period. Six gyros were put on board, although only three were needed to perform nominal operations. However, following anomalous behaviour of two gyros in 1996 and January 1997, it was decided to implement new pointing modes, with only one (one gyro mode) or no gyro (gyro-less mode) in the control loop of the attitude system. The one-gyro mode was successfully uploaded on August 1997 and operated at the same level of performances of the nominal mode (see e.g. Fig.3 and Fig.4) till near the end of the mission. On October 2001, the gyro-less mode was uploaded on board. This mode allowed to control the attitude of BeppoSAX without gyroscopes within the pointing and safety requirements of the mission, notwithstanding the increased drag with the atmosphere due to the lowering orbital altitude in the last months of the mission.

In the same period (well beyond the 2+2 years of lifetime originally planned) some of the battery cells showed anomalous behaviour. To cope with the more limited power, at the end of February 2002 the number of simultaneously operated instruments was reduced. Notwithstanding these problems, BeppoSAX carried out its observations till the switch-off. Actually, from the end of February till April 30 2002, BeppoSAX localized 5 GRB's (including one X-ray flash on Apr. 27), four of which were followed up with fast TOO's. This was one of the highest rate of localizations and TOO of GRBs during its entire lifetime.

Finally, as it happens for several space missions, convincing the financing bodies to extend operation beyond the nominal lifetime was another major challenge, successfully achieved in 2000 (extension to April 2001) and 2001 (extension to April 2002) with the strong support of national and international communities.

5. Scientific programme

In its six years of operations, encompassing 30715 orbits, BeppoSAX carried out about 1500 observations, for a total of 62 millions seconds with the Narrow Field Instruments, while the WFC and GRBM surveyed the sky in search of transients. All classes of X-ray sources were observed, but a substantial fraction (about 50%, see Fig.2) of the total observing programme was devoted to observations of compact galactic sources and AGN, i.e. the classes of sources mostly suited to the exploitation of the broad band spectral coverage of BeppoSAX Narrow Field Instruments (NFI, the set of co-aligned LECS, MECS, HPGSPC and PDS covering the 0.1-200 keV range). An example is shown in Fig.5. A significant effort was also dedicated by the project in arranging multi-wavelength observational campaigns, from radio to VHE, for several classes of objects (e.g. Fig.6) with results that well rewarded the investment.

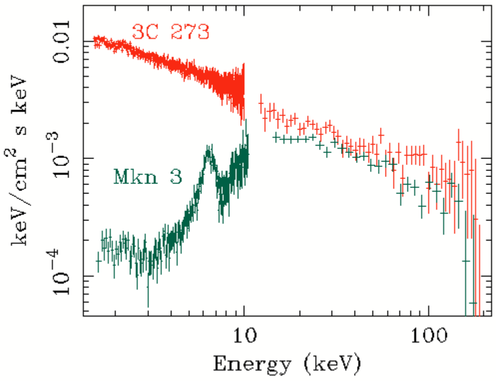

Fig. 5. The obscured accretion power in massive black holes. The broad band spectrum of two AGN, the quasar 3C273 and the heavily obscured Seyfert 2 galaxy Mkn3. Figure adapted from Cappi et al. (1999) and Grandi et al. (1997)

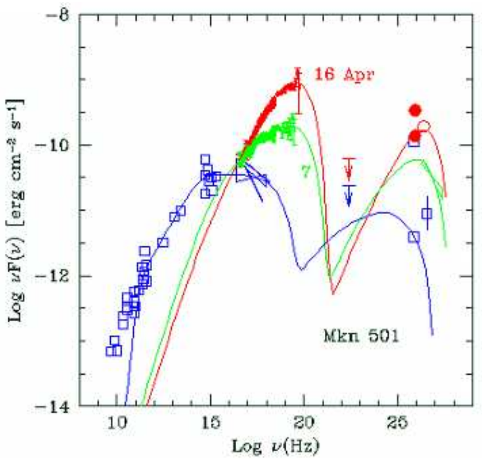

Fig. 6. Multiwavelenght campaign from radio to VHE of Mkn501 in quiescent and flaring states (Pian et al. 1998)

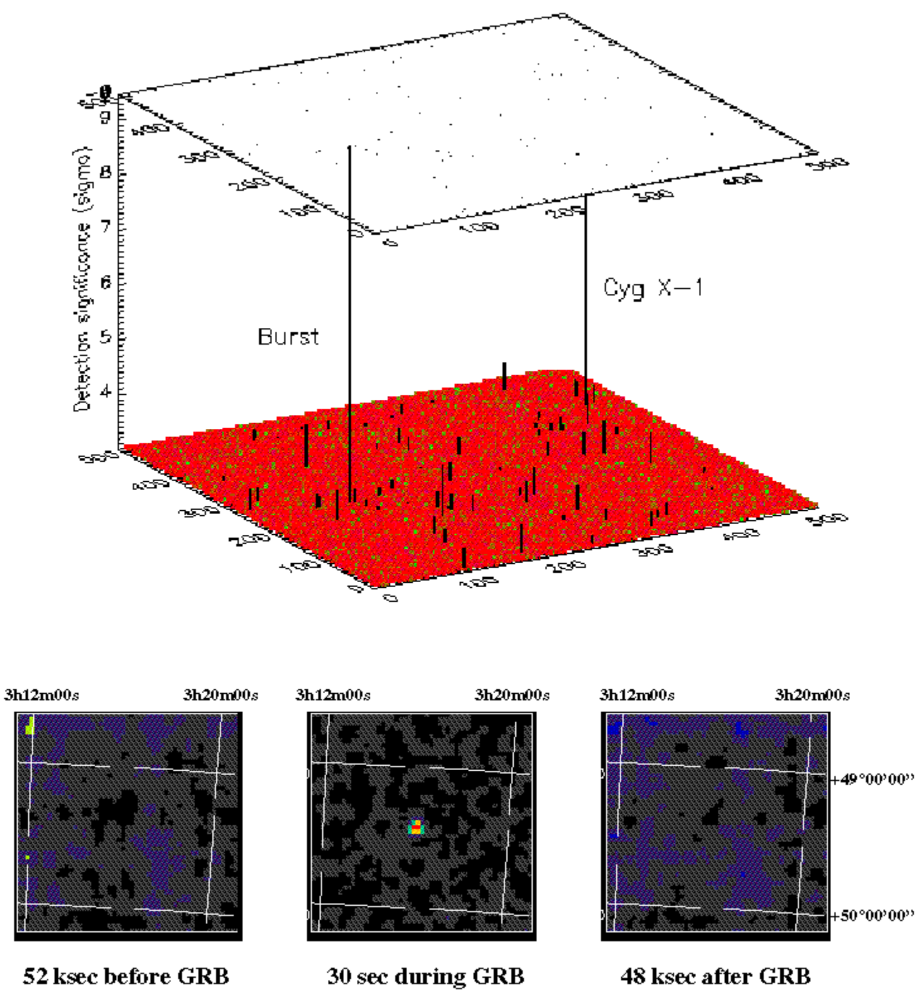

Fig. 7. The first GRB localized by BeppoSAX (Piro et al. 1998), GRB960720. Upper panel: The 40° ×40° image of the burst in the 2 − 26 keV range of the WFC integrated over 15 s during the burst. The y axis gives the significance of the detection (in standard deviations, σ). The source close to the edge is Cyg X-1. Lower panel: Images of the field centered on the burst in time sequence. The central image is a 30 s long shot during the burst, while the first and last images were obtained integrating over $\sim 50,000$ s before and after the burst.

The other strong asset of the mission was the capability of discover and carry out deep observations of transient phenomena in the sky. This was catered by wide field X-ray and gamma-ray monitors (Wide Field Cameras, WFC, and Gamma-Ray Burst Monitor, GRBM) coupled with a high level of flexibility of ground scientific operations in carrying out Target of Opportunity Observations (TOO) with NFI. In fact, a substantial part of the program was devoted to such observations: about 190 NFI observations (corresponding to a total of 7.2 Msec), out of which 2.2 Msec on Gamma-Ray Bursts.

The observing time was open to national and international communities, with 5 Announcements of Opportunity issued with an average overbooking factor of 4.5.

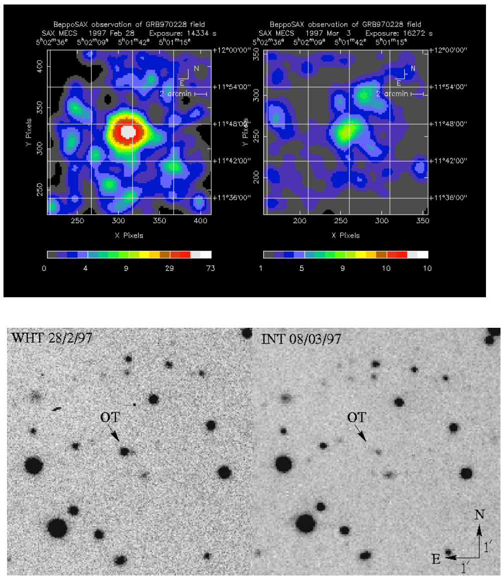

Fig. 8. Top: BeppoSAX MECS images of the GRB 970228 afterglow, 8 hours (left) and 3 days (right) after the GRB trigger (Costa et al. 1997). Bottom: Optical images taken with the WHT 21 hours after the burst (left), and with the INT on March 8 (right) (van Paradijs et al. 1997).

6. Gamma-Ray Bursts: a programmed fortune

The study of GRB was one of the main scientific goals of the mission since the beginning and thus not a sheer stroke of luck coming out of the blue. The possibility of localizing and then carrying out follow up observations of GRBs with the X-ray telescopes to search for their counterparts was anticipated before the launch (Piro et al. 1995b) (see also Piro et al. 1995a; Boella et al. 1997a). The possibility of deriving the position of GRBs with WFCs was stated in Perola (1985), while the full observational strategy, from GRB trigger and position to follow up observations was presented first in (Piro et al. 1995b). The latter reference reads, in the chapter titled *Transient searches and follow-up observations; gamma-ray burst....The combination of the WFC's and NFI on SAX offers the very exciting opportunity to detect new transients and to study in detail their evolution during their decay... For timely follow-up observations with the NFI it is essential that their discovery be recognized immediately. To this effect a service will be implemented to ensure a quick look analysis of all the relevant data of the WFC's... The PDS shield (i.e. the GRBM) will be used to monitor GRB with fluence greater than* 10^{-6}*erg cm*$^{-2}$*. On the basis of the CGRO/BATSE catalogue, about 60 burst per year are expected above the given fluence threshold. Furthermore, about 10 GRB with fluence greater than* 10^{-7}*erg cm*$^{-2}$ *(assuming* $f_X = 0.01 f_\gamma$*) are expected to fall in 3 years in the field of view of the WFCs and be detected: for these bursts a 5' position might also be obtained, along with spectral and temporal information on the X-ray tail of their emission.* The reaction time of BeppoSAX was also clearly indicated:..*The observing programme will be flexible in order to accomodate follow-up observations with the NFI of selected TOO. Due to the extremely flexible operating strategy, SAX will be able to acquire a new target within a few hours of its discovery*. Conservatively, however, we committed the project to a minimum guaranteed reaction time of 15 hours. It is interesting to note that, in this estimation of the number of GRB localized by the WFC, we were rather conservative, mostly because we used a low value of the X-to-gamma ray ratio. In the prediction made in 1982 (Perola 1985) the number derived was 10 per year, essentially the same as observed (56 GRBs in 6 years).

Thus a significant effort was put by the project in setting up ground operations to cope with a fast reaction to new transient phenomena discovered with wide field instruments, with particular regard to GRBs. Ground procedures for a prompt dissemination of GRB coordinates and fast follow up observations became fully operative on December 1996 and were carried out under the responsibility of the project scientist. In particular all the follow up observations of the first year were performed under the Project Scientist discretionary time. Three months after launch, still during the commissioning phase, the first GRB ever localized by BeppoSAX was detected with an offline analysis (Fig.7 Piro et al. 1998), demonstrating the designed capability of the mission. The first opportunity to implement the fast follow up procedure came on January 11, 1997, (Feroci et al. 1998). The error box of the GRB was pointed with the Narrow Field Instruments (NFI) telescopes 16 hours after the GRB. In the past, the fastest reaction had been of about 3 weeks. The possible association of one of the faint sources found in the error box was still under scrutiny, when on February 28, 1997, another event, the now famous GRB970228, was detected by BeppoSAX GRBM and WFC, leading to the discovery of the first X-ray and optical afterglows (Fig.8 Costa et al. 1997; van Paradijs et al. 1997). The ensuing events are well known (Piro & Hurley 2012). With the discovery of the afterglow, the distance scale of GRB was determined, and their association with massive star explosions in very distant galaxies established. Amongst the most important events following GRB970228 it is worth mentioning GRB970508, whose precise and fast localization (Piro et al. 1998) allowed the first determination of distance and the discovery of the first radio afterglow and observational evidence of a relativistic fireball (Metzger et al. 1997; Frail et al. 1997). Another event, GBR980425 (Pian et al. 2000), with its association with SN1998bw (Galama et al. 1998), demonstrated the association of GRB with SN. In summary, at the end of the mission, 56 GRB (including 8 X-ray rich GRB) were localized in real time by wide field instruments and their position distributed within few hours to the community via GCN and BeppoSAX mails. 38 GRB were observed with fast TOO observations (from 5 hrs to 1 day, with an average delay of around 8 hours) with NFI (see Fig.3 that reports the 36 TOO observations of GRB localized by BeppoSAX. Two other GRBs, GRB980723 and GRB000926 were observed following external triggers).

7. The BeppoSAX heritage

The scientific achievements of BeppoSAX are well documented in the literature (with more than 1500 papers published on international journals as of April 2002, see *www.asdc.asi.it/bepposax/publications.html*, and other 600 papers from the end of the mission to 2012), as well as by international awards given for the research on GRB (1998: Bruno Rossi Prize of the American Astronomical Society. 2002: Descartes Prize by the Commission of the European Union. 2010: Fermi Prize of the Italian Physical Society. 2011: Shaw Prize in Astronomy).

Along with scientific return (and the BeppoSAX archive is still a rich mine of data), the original requirement of the AO has been fully met: the national scientific and industrial communities have achieved and demonstrated the capability to build and manage ambitious space-based missions. In particular we recall, at instrument level, the X-ray optics developed by O. Citterio, that have found application in XMM, Jet-X/SWIFT, the consolidation of detector technology in the other institutes and the development of national space industry (amongst which we recall Alenia Spazio, prime contractor for the satellite, Telespazio, prime contractor for the ground segment, LABEN, for the scientific payload), with key participation to other space missions (e.g INTEGRAL of ESA). The heritage of BSAX includes the qualification of the ASI ground station in Malindi, used for several international and national missions (AGILE, SWIFT, HETE2, Fermi,), in the development of a BeppoSAX data center, that has now evolved in a ASI multi-mission facility (ASDC). Finally, the joint effort by CNR institutes of the SAX consortium (Roma, Bologna, Palermo, Milano) was one of the main drivers leading in 2000 to the constitution of a single institute (IASF).

Acknowledgements. BeppoSAX, a major program of the Italian space agency (ASI) with participation of the Dutch space agency NIVR, was carried out by many enthusiastic scientists, technicians and managers from scientific institutes, industries and the national space agencies. The author acknowledges helpful comments by G. Setti on the historical part of this paper.

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