ABSTRACT
Recent results on Gamma-Ray Bursts obtained with the X-ray Astronomy satellite BeppoSAX are reviewed. Main emphasis is given to the GRBs simultaneously detected with the Gamma-Ray Burst Monitor (40–700 keV) and the Wide Field Cameras (1.5–26 keV). These bursts were rapidly localized with high precision, which permitted a prompt pointing of their error boxes with the Narrow Field Instruments aboard the same satellite. In three cases of bursts, these prompt observations led to the discovery of an X-ray afterglow. For two events also an optical transient was discovered. We review these results and their implications.

INTRODUCTION
The nature and the origin of celestial Gamma-Ray Bursts (GRB) is recognized to be one of the major challenges of high energy astrophysics. Before the launch of BeppoSAX, we knew that they are isotropically distributed in the sky, while their number versus intensity distribution is not homogeneous in the space volume accessible to the GRB detectors, with a deficit of faint bursts (Fishman and Meegan, 1995). A wealth of information about GRB energy spectra and temporal features has been obtained since their first discovery by Klebesadel et al. (1973), with several satellite missions and, in particular, with the Compton Gamma Ray Observatory (CGRO) (see, e.g., Preece et al. 1996, Norris et al. 1996, Crider et al. 1997 and references therein). In spite of these efforts, many scenarios on the nature of the bursts are compatible with these data, given the uncertainty on the sites and distance of these events. Only the detection of an X-ray or optical counterpart represents the needed breakthrough to explain the GRBs phenomenon. Thanks to the presence aboard the BeppoSAX satellite (Boella et al., 1997a) of a Gamma-Ray Burst Monitor (GRBM) with a trigger system in case of GRB detection and two Wide Field Cameras (WFC, 1.5 -26 keV, Jager et al., 1997) capable to quickly provide accurate source positions within a few arcmin in a field of 40° × 40°, we can provide in few hours GRB celestial coordinates and to point the BeppoSAX Narrow Field Instruments to the GRB error box to search for X-ray afterglows. Thus far 5 GRBs have been simultaneously detected with GRBM-WFC, four of which have been promptly (< 20 hrs) re-observed. In three cases an X-ray afterglow was clearly discovered and in two cases also the optical counterpart was detected by ground-based telescopes. In this paper we review these results and their implications.

THE BEPPOSAX SATELLITE
SAX (Italian acronym of X-ray Astronomy Satellite) (see Figure 1) is a major program of the Italian
The main capability of the mission is to perform spectroscopic and timing studies of galactic and extragalactic X-ray sources in a broad energy band (0.1-300 keV) with well balanced instrument performances over the full band. In the range from 0.1 to 10 keV BeppoSAX can perform spatially resolved studies of extended sources (e.g., supernova remnants) with 1 arcmin angular resolution and spectral resolving power $E/\Delta E$ in the range from 5 to 10. Also wide sky regions with arcminute angular resolution in the range from 2 to about 30 keV can be monitored. Finally a capability for detecting celestial Gamma-Ray Bursts (GRBs) is also provided.

To achieve all these capabilities, the satellite includes both narrow and wide field instruments. The Narrow Field Instruments (NFI) include two telescopes and two direct viewing detectors. The two telescopes are the Low Energy Concentrator Spectrometer (LECS), that operates in the 0.1 to 10 keV (Parmar et al. 1997) and the MECS (three units) that operates in the band from 1.5 to 10 keV (Boella et al. 1997b). Both make use of X-ray optics. The two direct-viewing detectors are the High Pressure Gas Scintillator Proportional Counter (HPGSPC), that operates in the band from 3 to 60 keV (Manzo et al. 1997) and the Phoswich Detection System (PDS), that operates in the 12-300 keV energy band (Frontera et al. 1997). The NFIs have their axes coaligned. Their field of view ranges from 1.3° (FWHM) for PDS to 30 arcmin for the telescopes.

The wide field instruments include two Wide Field Cameras (WFCs) and a Gamma-Ray Burst Monitor (GRBM). Both have their axis orthogonal to the NFIs. The WFCs are two coded mask proportional counters that look in opposite directions. They operate in the energy band from 1.5 to 26 keV with a field of view of $20^\circ \times 20^\circ$ (FWHM) and imaging capability with an angular resolution of 3 arcmin. The GRBM is a part of the PDS experiment. It is made of four slabs of CsI(Na) scintillators 10 mm thick, that surround the core of PDS. The GRBM field of view is almost completely open to the sky. The surface area of each detection unit is 1100 cm$^2$. The four scintillators are also used as anticoincidence shields of the PDS. The GRBM has a dedicated electronics with a trigger system for fast transient events. Details on the instrument can be found in the proceedings of this conference (Frontera et al. (1997b) and elsewhere (e.g., Feroci et al. 1997). The GRBM effective energy band is from 40 to 700 keV. A configuration of the BeppoSAX payload is shown in Figure 2.

The satellite was launched on 30 April 1996 from Cape Canaveral (Florida, USA) with an Atlas-Centaur rocket. Its orbit is almost equatorial (inclination = 3.9°) at an altitude of about 600 Km. The data are stored on board and transmitted to the ground after each orbit, when the satellite is visible from the ground station in Malindi, Kenya. Via a relay satellite (Intelsat), these data are immediately transmitted to the Operative Control Center (OCC), located in Rome, Italy. The link with BeppoSAX is also used in order to upload telecommands and receive direct telemetry.
The payload configuration described above makes BeppoSAX highly suitable for the study of GRBs. From one side we have two detection units of the GRBM with their axis parallel to those of WFCs with the possibility of monitoring about 5% of the sky with two complementary instruments. Counts variations in the WFCs can be recognized to be due to GRBs and distinguished from, e.g., X-ray burster events, from their simultaneous detection with the GRBM. On the other side, the presence on the same satellite of NFIs with focusing optics affords the possibility to rapidly perform high sensitivity observations of GRB error boxes provided by the GRBM/WFC detections.

The GRBM trigger threshold for bursts along the WFC field of view corresponds to a flux of about $0.6 \, \text{photons cm}^{-2} \, \text{s}^{-1}$, equivalent to about $1 \times 10^{-7} \, \text{erg cm}^{-2} \, \text{s}^{-1}$. Currently the trigger system is set for long bursts ($\geq 1 \, \text{s}$). For the triggered bursts, time profiles with high time resolution (down to 0.48 ms) are stored. Continuously we transmit, for each GRBM detection unit, 1 s time profiles in two partially superimposed energy bands (40–700 keV and $> 100 \, \text{keV}$) and 220 channel energy spectra collected over 128 s.

The WFC sensitivity in 3 s is about $1 \times 10^{-8} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ corresponding to about 0.3 Crab flux unit. The error radius in the GRB positioning is $\leq 3 \, \text{arcmin}$.

Since December 1996, at the BeppoSAX Science Operation Center (SOC) an alert system is implemented for each simultaneous GRBM/WFC detection of fast transients events. Following the verification of an actual detection of a GRB, a Target of Opportunity (TOO) pointing of the BeppoSAX NFIs is performed. The minimum time delay between the first TOO pointing and the initial event can be about 5 hrs.

### Table 1: Gamma-Ray Bursts simultaneously detected with BeppoSAX GRBM and WFCs

| Event    | TOO time (hrs) from the event | GRB peak flux 40–700 keV (erg cm$^{-2}$ s$^{-1}$) | GRB peak flux 2–26 keV (erg cm$^{-2}$ s$^{-1}$) | Afterglow source |
|----------|-----------------------------|-----------------------------------------------|-----------------------------------------------|------------------|
| GRB960720 | 1038                        | $1.7 \times 10^{-6}$                         | $2.5 \times 10^{-8}$                         | QSO 4C 29.29 (?) |
| GRB970111 | 16                          | $5.6 \times 10^{-6}$                         | $1.4 \times 10^{-7}$                         | $\leq 5 \times 10^{-14}$ |
| GRB970228 | 8                           | $3.7 \times 10^{-6}$                         | $1.4 \times 10^{-7}$                         | 1SAX J0501.7+1146 |
| GRB970402 | 8                           | $3.2 \times 10^{-7}$                         | $1.6 \times 10^{-8}$                         | 1SAX J1450.1-6920 |
| GRB970508 | 5.7                         | $5.6 \times 10^{-7}$                         | $3.5 \times 10^{-8}$                         | 1SAX J0653.8+7916 |

**RESULTS OF GRBM/WFC SIMULTANEOUS DETECTIONS OF GRBs**

Table 1 shows a summary of the simultaneous detections of GRBs obtained thus far with the BeppoSAX GRBM and WFC instruments. For each of these detections a TOO observation with the NFIs was performed. The second column of Table 1 shows the time delay between the first TOO observation and the initial event. As can be seen, the time delay is very long for the first event detected (GRB960720) and very short for the last event (GRB970508). The long time delay (about 43 days) for the TOO following the first event is due to the fact that the first simultaneous GRBM/WFC detection occurred during the Science Verification Phase of the satellite and thus was discovered during the off-line analysis. The other columns of Table 1 show, for each event, the $\gamma$-ray (40–700 keV) and
X-ray (2–26 keV) peak fluxes achieved during the bursts and the result of the TOO observations. The γ-ray time profiles of the last four bursts observed are shown in Figure 3.

Now we discuss highlight results obtained for each event.

GRB960720
The event occurred on July 20, 1996 at 11:36:53 UT. Initially its position was first determined with an error radius of 10 arcmin (Piro et al. 1996). Successively, with a more refined analysis, the event was located in an error circle centred at α_{2000} = 17\text{h} 30\text{m} 36\text{s} and δ_{2000} = +49° 05' 49'' with 3 arcmin error radius (in 't Zand et al. 1997). The burst fluence was 2.5 \times 10^{-6} \text{erg cm}^{-2}. A long observation (56 ks) of the 10 arcmin error circle was performed on September 3, 1996 with the NFIs. Results of this observation and properties of the burst are reported elsewhere (Piro et al. 1997a).

A faint X-ray emission in the error box (F(2–10 keV) = (1.0 \pm 0.3) \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}) was found to be consistent with the direction of the strong radio loud quasar 4C 49.29 (f(408 MHz) = 2 Jy and m_V = 18.8). The ratio of the measured X-ray flux with the optical one is that typical of a quasar (Maccacaro et al. 1980). Thus it is not immediately possible to relate the measured X-ray emission to an X-ray afterglow from GRB960720.

GRB970111

This event was detected on January 11, 1997 at 09:44:00 UT. It was the strongest of the simultaneous GRBM/WFC detections (see Table 1 for peak flux) with a total fluence in the 1.5–700 keV energy band of 6.8 \times 10^{-5} \text{erg cm}^{-2}. Its γ-ray time profile is shown in Figure 3. This burst was the first event localized with the quick look analysis procedure. Initially its position was established with a 10 arcmin error radius at the celestial coordinates α_{2000} = 15\text{h} 28\text{m} 24\text{s} and δ_{2000} = +19° 40' 00'' (Costa et al. 1997a). Soon after the event, a BeppoSAX TOO observation of the above error box was approved. The pointing with the NFIs started 16 hrs after the main event. Two sources (A and B) in the WFC error box were discovered (Butler et al. 1997). The ROSAT all-sky survey data taken in the time period 5–7 August 1991 showed that in the same error box three sources (1, 2 and 3) were detected (Voges et al. 1997). By comparing the positions of the ROSAT with those of the SAX sources, it resulted that the SAX source A was resolved into the ROSAT

Fig. 3: Time profiles of the GRBs detected with BeppoSAX GRBM and WFC, for which a prompt follow-up with the NFIs was performed.

Fig. 4: WFC preliminary and improved error circles of GRB970111 along with IPN BATSE/Ulysses error annulus superposed to a radio continuum image at 1.4 GHz centred on the preliminary GRB centroid position. Position of the BeppoSAX sources A and B (small open circles) and VLA sources are also shown. (From Frail et al. 1997b.)
Sources 1 and 2, while the SAX source B was coincident with the ROSAT source (Voges et al. 1997). The event was also detected with the GRB detector aboard the Ulysses interplanetary mission and with the BATSE experiment aboard the CGRO satellite. By using the time delay between these two detections, Hurley et al. (1997a) derived an error annulus for the burst position that reduced the 10 arcmin error circle to a trapezoidal error box. In this new error box only SAX source A ($\alpha_{2000} = 15^h 28^m 46^s$ and $\delta = +19^\circ 44' 50''$) was contained. The source A appeared a good candidate as X-ray counterpart of the GRB970111 afterglow also considering that a VLA variable radio source (J1528.7+1945) coincident with the X-ray position was discovered (Frail et al. 1997a). However, after a more refined analysis of the WFC data, the GRB error box was further reduced with a change of the centroid position (in 't Zand et al. 1997). The new error circle had a 3 arcmin error radius and was centred at $\alpha_{2000} = 15^h 28^m 15^s$ and $\delta = +19^\circ 36' 18''$. In the improved error box neither X-ray sources or variable radio or optical candidate objects were observed (Frail et al. 1997b, Castro-Tirado et al. 1997a). The $3\sigma$ upper limit to X-ray emission is reported in Table 1. Figure 4 shows the WFC (preliminary and refined) error boxes with the Interplanetary Network (IPN) error annulus and the X-ray (BSAX) and radio (VLA) source positions.

**GRB970228**

The gamma-ray burst GRB970228 was the first event for which an X-ray afterglow was discovered. The BeppoSAX GRBM was triggered by this event on February 28, 1997 at 02:58:00 UT (Costa et al. 1997b).

Its position was first determined with a 10 arcmin error radius and then with a radius of 3 arcmin ($3\sigma$) centred at $\alpha_{2000} = 05^h 01^m 57^s$, $\delta_{2000} = 11^\circ 46' 24''$. Eight hours after the GRB trigger, from February 28.4681 to February 28.8330 UT, the NFI's were pointed to the WFC error box. An X-ray source, SAX J0501.7+1146, was detected (Costa et al 1997c) in the field of view of both the LECS and MECS telescopes. The source position ($\alpha_{2000} = 05^h 01^m 44^s$, $\delta_{2000} = 11^\circ 46' 42''$) was consistent with the GRB error circle. No previous detection of this source was obtained with the ROSAT all-sky survey (Boller et al. 1997). The source was again observed about three days later, from March 3.7345 to March 4.1174 UT. During this observation the 2-10 keV source flux had decreased by about a factor 20 while it was not detected in the 0.1–2 keV energy band. Figure 5 shows the image of the source in the 2-10 keV band, during the first and the second TOO, obtained with the MECS telescope. Following this discovery, searches for radio and optical counterparts of GRB970228 were started with many ground-based telescopes located in the Northern hemisphere. Galama et al. (1997) first reported the discovery of an optical transient at a position ($\alpha_{2000} = 05^h 01^m 46.66'$, $\delta_{2000} = 11^\circ 46' 53.9''$) consistent with both the BeppoSAX WFC and NFI error circles and with the annuli obtained from the time delay in the detection times of the burst with Ulysses and BeppoSAX (Hurley et al. 1997b) and with Ulysses and GGS-Wind experiment (Cline et al. 1997). Figure 6 shows the sky position of the optical transient (WHT) along with various error boxes. An X-ray observation with the ROSAT HRI instrument of the WFC error box, performed between March 10.7875
and March 13.32 UT, detected a previously unknown source, whose centroid position (error circle 10 arcsec) was consistent with the SAX source and coincident with the optical transient position within 2 arcsec (Frontera et al. 1997c). This result makes the association of the optical transient with the SAX source, and thus with the afterglow of GRB970228, very compelling (Frontera et al. 1997d). The X-ray afterglow shows very interesting features. The decay curve of the 2-10 keV flux from 1SAX J0501.7+1146 (see Figure 7) is consistent with a power law ($t^{-\alpha}$) with $\alpha = 1.33^{+0.13}_{-0.11}$ (Costa et al. 1997d). When the decay curve is extrapolated backward to the GRB time, we find that its value is consistent with the average flux of the last three pulses of the burst (see Figure 3). This fact makes the identification of the fading X-ray source with GRB970228 very compelling. A power law temporal decay function with similar slope is predicted for the X-ray flux emitted by a forward blast wave moving ahead of a relativistically expanding fireball, when it decelerates by ploughing into the surrounding medium (Mészáros and Rees 1997, Wijers et al. 1997). In this model the power law slope is expected to be independent of the photon energy.

The spectral evolution of the burst and its X-ray afterglow show that the nature of the X-ray afterglow emission is of non thermal origin and similar to the later portion of the burst emission. (Frontera et al. 1997e). Thus models that assume that GRB phenomenon is due to cooling of neutron stars can be ruled out and fireball models are further constrained in their radiation emission processes.

The optical transient associated with GRB970228 was also observed with the Hubble Space Telescope (HST) 26 and 39 days from the initial event. At these epochs the source was no more detectable from ground based telescopes. A point-like object embedded in an extended nebulosity of about 1 arcsec extension was seen in both V and I bands (Sahu et al. 1997). While the point-like object appeared to decline from the first to the second observation, the emission from the extended source was consistent with a constant value. If the extended component is interpreted as the host galaxy of the optical transient, this result would be in favour of an extragalactic origin of GRB970228. Actually Caraveo et al. (1997), using the above HST observational data, reported the detection of a proper motion of the optical transient. They estimate a variation of the transient position by $(18\pm5) \times 10^{-3}$ arcsec in 12 days. At the time of writing this paper a further observation of the optical transient with HST, performed in September 4, has shown for the point-like source no proper motion larger than 100 milli-arcsec/year (Fruchter et al. 1997) disproving the previous claims by Caraveo et al. (1997). The above HST observation also confirms the presence of an extended optical nebulosity superposed to the point-like object (Fruchter et al. 1997). While the intensity of the latter continues to decline with a power law similar to that in the X-ray band, the intensity of the nebulosity is consistent with that measured in the March/April observation (Fruchter et al. 1997).

**GRB970402**

The GRBM detector was triggered by this burst (see Table 1 and Figure 3) on April 2, 1997 at 22:19:39 UT (Feroci et al. 1997). It is the weakest GRB detected with GRBM and WFC thus far. Its time
The profile is complex with a long time duration (about 120 s). The event position was determined with a 3 arcmin error radius at the celestial coordinates $\alpha_{2000} = 14^h 50^m 16^s$ and $\delta_{2000} = -69^\circ 19' 54''$ (Heise et al. 1997a). After 8 hrs from the initial event a pointing with the NFIs was performed. A previously unknown X-ray source, 1SAX J1450.3-6919 ($\alpha_{2000} = 14^h 50^m 06^s$ and $\delta_{2000} = -69^\circ 20' 00''$) was discovered. A re-pointing of BeppoSAX to the source direction after 1.8 days did not show any emission. For comparison another source, 1SAX J1448.2-6920, that was in the field, was visible in both pointings (Piro et al. 1997b).

The decay of the source X-ray flux with time is consistent with a power law with index similar to that of the GRB970228 afterglow time decay (Nicastro et al. 1997). Prompt observations of the GRB error box with optical, IR and radio telescopes did not give any positive result (Castro-Tirado et al. 1997b).

GRB970508

The third X-ray afterglow was observed from the burst GRB970508. This event was detected by GRBM on May 8, 1997 at 21:41:50 UT. (Costa et al. 1997e). GRB peak fluxes are given in Table 1. As can be seen, the event is weak with peak flux comparable to that of the April event. However the $\gamma$-ray time profile is very different (see Figure 3) with a single pulse and a much shorter duration (about 20 s). The refined position of the event, obtained with BeppoSAX WFC, is $\alpha_{2000} = 06^h 53^m 46.7^s$ and $\delta_{2000} = -79^\circ 16' 02''$ with an error radius of 50''. In the same field, another source known from the ROSAT all-sky survey, 1RXS J0653.8+7916, was also detected. After this first TOO, three other observations were performed about 3, 4 and 6 days from the initial event. In the 2-10 keV energy band the flux decline had a different behaviour from that of the afterglow source associated with GRB970228. Combining together WFC data and TOO results, the scenario is of a source that appears to decline according to a power law with $\alpha \sim -1.1$ until the time of the first TOO, when a transient event of about $10^5$ s duration superimpose to the above law (Piro et al. 1997d).

This peculiar time behaviour of the X-ray afterglow is accompanied by a similar complex behaviour of the optical variable (OT J065349+79163) discovered by Bond (1997), that has been proposed as probable optical counterpart of 1SAX J0653.8+7916 (Djorgovski et al. 1997). The optical transient, after an indication of decay, showed a flux rise at the same time as in X-rays. Only about 2 days after the the burst, it showed a definitive decay with a power law function with index $\alpha = -1.13 \pm 0.04$.
A result of primary importance concerning this GRB is the discovery of redshifted absorption lines in the optical spectrum of OT J065349+79163 (Metzger et al. 1997). These observations were performed at the Keck II 10-m telescope on 11 and 12 May 1997. The source continuum spectrum is characterized by a prominent metal absorption line system (mainly Fe II, Mg I and Mg II) as well as [O II] emission line with wavelengths redshifted by $z = 0.835$. The detection of Mg I absorption suggests the presence of a dense interstellar medium, while the presence of [O II] emission line suggests stellar formation. Both features suggest the presence of a galaxy. As a consequence of this result, the continuum source is either more distant and absorbed by a gas cloud at this redshift, or is located within the cloud. In any case the lower limit to the OT J065349+79163 redshift is 0.835. This is the first determination of the distance to a GRB.

CONCLUSIONS

The presence of the X-ray afterglow appears an almost common feature of GRBs. Three of 4 GRBs that were promptly re-observed with the BeppoSAX NFIs showed X-ray afterglow emission. The burst peak fluxes cover a large fraction of the log N-log P distribution derived from the BATSE GRB catalog (Meegan et al. 1996). In addition they span an order of magnitude in time durations and show different time profiles. These features do not seem to be relevant for the presence or absence of X-ray afterglow emission. From only one burst, GRB970111, we did not detect any X-ray afterglow emission after 16 hrs. This could be related to a faster decline of the X-ray afterglow emission than in the other bursts or could be intrinsic to the phenomenon itself. The decline of the X-ray afterglow emission with time is a power law in two cases and more complex in one case (GRB970508). One possible explanation of the complex time behaviour of the GRB970508 X-ray and optical afterglow is the occurrence of an impulsive event with much longer time scale (about $10^5$ s) about $3 \times 10^4$ s from the initial event. This second event could have modified the power law time decay related to the initial burst (Piro et al. 1997d).

From the optical results, it appears very likely that both GRB970228 and GRB970508 have extragalactic origin. As we discussed in section 3.3, the extragalactic origin is also in agreement with the fireball models (Mészáros and Rees 1997, Wijers et al. 1997). We expect other simultaneous GRBM/WFC detections of GRBs and thus other detections of GRB afterglows in other bands of the electromagnetic spectrum in order to clarify several aspects of the GRB phenomenon that are still unclear.
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