The SXI telescope on board EXIST: scientific performances

L. Natalucci\textsuperscript{a}, A. Bazzano\textsuperscript{a}, S. Campana\textsuperscript{b}, P. Caraveo\textsuperscript{c}, R. Della Ceca\textsuperscript{b}, J.E. Grindlay\textsuperscript{d}, F. Panessa\textsuperscript{a}, G. Pareschi\textsuperscript{b}, B. Ramsey\textsuperscript{e}, G. Tagliaferri\textsuperscript{b}, P. Ubertini\textsuperscript{a}, G. Villa\textsuperscript{c}

\textsuperscript{a}INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, Sezione di Roma, via Fosso del Cavaliere 100, I-00133 Roma, Italy;
\textsuperscript{b}INAF-Osservatorio di Brera, via Bianchi 46, I-23807 Merate, Italy;
\textsuperscript{c}INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, Sezione di Milano, Via E. Bassini 15, I-20133 Milano, Italy
\textsuperscript{d}Harvard-Smithsonian CfA, 60 Garden Street, Cambridge MA 02138, USA
\textsuperscript{e}NASA Marshall Space Flight Center, VP62, Huntsville, AL 35812, USA

ABSTRACT

The SXI telescope is one of the three instruments on board EXIST, a multiwavelength observatory in charge of performing a global survey of the sky in hard X-rays searching for Supermassive Black Holes. One of the primary objectives of EXIST is also to study with unprecedented sensitivity the most unknown high energy sources in the Universe, like high redshift GRBs, which will be pointed promptly by the Spacecraft by autonomous trigger based on hard X-ray localization on board. The recent addition of a soft X-ray telescope to the EXIST payload complement, with an effective area of 950 cm\textsuperscript{2} in the energy band 0.2-3 keV and extended response up to 10 keV will allow to make broadband studies from 0.1 to 600 keV. In particular, investigations of the spectra components and states of AGNs and monitoring of variability of sources, study of the prompt and afterglow emission of GRBs since the early phases, which will help to constrain the emission models and finally, help the identification of sources in the EXIST hard X-ray survey and the characterization of the transient events detected. SXI will also perform surveys: a scanning survey with sky coverage $\sim 2 \pi$ and limiting flux of $\sim 5 \times 10^{-14}$ cgs plus other serendipitous. We give an overview of the SXI scientific performance and also describe the status of its design emphasizing how it has been derived by the scientific requirements.

Keywords: X-ray telescopes, EXIST, X-ray Instrumentation

1. INTRODUCTION

The potential of surveys in high energy astronomy is being fully demonstrated by the sky observations performed at X- and soft $\gamma$-ray wavelengths during the last decade. In particular XMM Newton\textsuperscript{1} with its deep sensitivity in the soft X-ray band, INTEGRAL\textsuperscript{2} and Swift\textsuperscript{3} up to $> 100$ keV have started to reveal the demographics of sources in the near Universe by studying populations of objects. Still lacking today are both a comprehensive picture of transient phenomena (other than GRBs) spanning a broad range of durations and a deep study of the supermassive objects and their host galaxies against Universe age. Studies of transients require fast repointing and improved sensitivity for proper investigations of their prompt emission. The fast follow-up capability of Swift allows to probe the farthest regions of the Universe by the study of Gamma-Ray Bursts (GRB) and also to discover new populations of transients in our Galaxy. GRBs are today the only beacons that can be used to observe the Universe at $z > 3 - 4$, as demonstrated by Swift e.g. with the latest detection of a GRB at $z=8$. Swift has opened a new window on the far Universe with GRBs, but many more objects are needed including AGNs.

Swift also carries an X-ray telescope which is an unvaluable tool to observe the GRB afterglows (and Swift has demonstrated that almost all the GRBs have X-ray afterglows). The Swift/XRT telescope\textsuperscript{4} is also a powerful tool for localization of the sources seen by Swift/BAT and INTEGRAL/IBIS\textsuperscript{5} at hard X-ray energies. In the case of IBIS, of the 167 new sources in the 3rd IBIS catalog\textsuperscript{6} 129 have been identified through optical and NIR

\textsuperscript{1}Further author information: (Send correspondence to L.Natalucci)
L.Natalucci: E-mail: Lorenzo.Natalucci@iasf-roma.inaf.it, Telephone: +39 06 4993 4461
spectroscopy. Of these, more than 60% have been localized by XRT with typical accuracy $< 2 - 3$ arcsec. Most of the reasons for this success is the possibility for XRT to perform many, relatively short observations.

The concept of operability of Swift is also adopted in the design of the Energetic X-ray Imaging Survey Telescope (EXIST) mission. EXIST is a proposed hard X-ray imaging all-sky deep survey mission and was recommended by 2001 Report of the Decadal Survey. It is a strong candidate to be the Black Hole Finder Probe, one of the three "Einstein Probes" in the Beyond Einstein Program, now proposed for the Astro2010 Decadal Survey. EXIST will be launched in a Low Earth Orbit (LEO) and its primary instrument is the High Energy Telescope (HET), a wide field coded aperture instrument covering the 5-600 keV energy band and imaging sources in a $\sim 70 \times 90 $deg$^2$ field of view with 2 arcmin resolution and better than 20 arcsec positions. The energy band of HET overlaps with the soft X-ray range covered by the proposed Soft X-ray Imager (SXI), 0.1-10 keV with an effective area of 950cm$^2$ at 1.5 keV and 3.5m focal length. At longer wavelengths, the IRT is an optical-IR aperture telescope covering the 0.3 – 2.2 micron range with variable spectral resolution and high sensitivity (AB=24 in 100s). The IRT pixel size is 0.15 arcsec and its Field-of-View in Imaging mode is 16 arcmin$^2$. So EXIST is a real multiwavelength observatory for observations of GRBs and Supermassive Black Holes (SMXB) as well as of many other types of transients and high energy sources.

In the following we will address some of the topics that will be contributed by the SXI telescope in the study of the high energy sources seen by HET and its capabilities for sky survey at soft X-ray wavelengths. Section 2 contains a brief description of the SXI telescope and its effective area, Section 3 and 4 will describe some of the science cases relevant to SXI.
2. THE SXI DESIGN

The proposed design is based on a Wolter type-I telescope consisting of a main mirror assembly with 26 nested cells and a focal plane camera with CCD detector. The focal plane distance is 3.5m and the max.diameter of the mirrors is 60cm (giving 70cm on the telescope outer envelope). The telescope structure, shown in Fig 1 (top) is built around an I/F flange in titanium which is the unique interface to the satellite optical bench. The mirror system and camera are also shown in the same figure (bottom).

The structure consists of a forward tube holding the mirrors and a rear conical tube holding the camera, with a single spider on which the mirrors are mounted. Below the spider there will be an electron diverter and on top of the mirror system a pre-collimator will reduce the intensity of stray light. The camera design is very similar to the XRT and XMM-EPIC design. A CCD sensor and its Proximity Electronics are “suspended” in an Al shield and an active cooling system will ensure the optimal temperature for CCD operation. The sensor will be required to have a frame readout between 5 and 10ms (see Section 3). The camera contains other subsystems like the Vacuum Chamber, Filter Wheel and Vacuum Door. More information on the technical design of SXI can be found in a related paper\textsuperscript{10}.

In Figure 2 is shown the effective area of the telescope, obtained convolving the effective area of the mirrors with a suitable filter and with the response of the pn-CCD similar to XMM. The effective area is similar to the one of an XMM module for $E < 2$ keV, losing efficiency at higher energies due to lower focal length. The parameters of the baseline design of SXI are reported in Table 1.

3. OPERATION OF THE SXI TELESCOPE

In analogy with Swift/XRT, SXI will operate with different modes, the count rate threshold of which basically depends on the performance of its detector. A Photon Counting (PC) mode will be used to observe sources up to $\sim 50 - 100$ mCrabs, whereas more intense sources will be monitored by means of other modes allowing for pileup. The main difference with respect to the XRT telescope is the possibility of operation during continuous scans. During the first two years EXIST will be programmed for a full sky survey of HET. With its large FOV the HET is capable of a full sky coverage each two orbits, by performing a continuous scan while pointing at the zenith. The last three years will be instead dedicated to inertial pointing observations, mainly of the sources detected by the HET in the first two year’s survey.
Table 1. Design parameters of the SXI telescope.

| Parameter          | Baseline                                      |
|--------------------|-----------------------------------------------|
| Mirror             | 26 shells                                     |
| Angular Resolution | 20 arcsec at 1 keV                           |
| Energy Range       | 0.1-10 keV                                    |
| Diameter of Mirror | 60cm                                          |
| Focal Length       | 3.5m                                          |
| Detector Type      | pn-CCD                                        |
| Detector Size      | 3x3 cm²                                       |
| FOV                | 30x30 arcmin²                                 |
| Energy Resolution  | 130eV at 6 keV                                |
| Readout Speed      | 5-10 ms                                       |
| Effective Area     | 950 cm² at 1.5 keV, > 100 cm² at 8 keV        |
| Sensitivity (10⁴s) | 2 × 10⁻¹⁵ cgs                                  |

Figure 3. Sky coverage/square degree, for a narrow field instrument during one year of HET scanning survey. The coverage is seen as a function of declination. A large fraction of the sky, comprised between -40 and 40 degrees declination will be amenable to SXI observation. The average time for each source in a SXI field will be ∼ 200s each year.
3.1 The SXI Scanning Survey

During HET scanning, the spacecraft is zenith-pointed with an offset of 30 degrees, towards the north and towards the south on alternate orbits. In the meanwhile, SXI will record events and the fast readout of its detector will allow to locate their direction within a few arcsec. The coverage of the SXI scanning survey is shown in Figure 3. In the plot is shown the sky coverage (calculated per square degree) of a narrow field instrument co-aligned with HET during one year of zenith scanning. The resulting average exposure time for a source being of the order of 200s/year, it is estimated that SXI will cover half of the sky with a limiting sensitivity of $\sim 5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in two years. The limiting sensitivity of the survey allows to investigate a high number of sources (a few hundred thousand).

As during the scanning survey the IRT is not expected to be active, SXI will be able to improve localization of many faint HET sources detected during the first two years: from $\sim 20$ arcsec to a few arcsec.

3.2 Pointing and Serendipitous Surveys

During the second phase of the EXIST mission, lasting 3 years it is expected to point at individual sources to acquire broadband images and spectra of the HET survey objects. This will allow for simultaneous broadband observations covering optical/NIR, soft X-ray to soft $\gamma$-ray bands. The SXI telescope as well as the IRT will measure source intensities and spectra for the hard X-ray sources observed by HET down to a sensitivity limit of $\sim 0.1$ mCrab in the hard X-ray band.

During observations of individual targets, SXI will be able to detect serendipitous sources in its field of view, at least if the initial target flux is not bright enough to allow operation in Photon Counting mode. If the typical observation time for this pointing phase is assumed to be $\sim 10^4$s, then assuming $\sim 2000$ observations each year it will be possible to cover $\sim 1500$ cm$^2$ during the 3 years of the inertial pointing phase, down to the sensitivity limit of $\sim 2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. For comparison, the most populated catalog ever made at X-ray wavelengths is that of XMM-Newton, with 191,870 sources and a sky coverage of 360 square degrees$^{11}$. Another serendipitous survey will be based on the detection of serendipitous sources for GRB repointing.
4. STUDIES OF INDIVIDUAL POINT SOURCES

EXIST being a powerful multiwavelength observatory, it will allow to obtain 0.1-500 keV broadband spectra for ∼ 500 or even more AGN with extension to the optical/NIR band. In Figure 4 (left panel) is shown the luminosity/redshift distribution of the AGNs detected by IBIS, corresponding to a survey with a limiting sensitivity of ∼ 1 mCrab in the 20-100 keV band\textsuperscript{12}. The most distant objects detected so far are the blazars, while type I and II objects, including absorbed and Compton thick sources are located in the region $z < 0.2$.

4.1 Broadband spectra for AGN studies

EXIST can study in much more detail the above objects in both number and quality of broadband spectra. Example spectra of individual objects observations are shown in Figure 4 (right panel) for two Compton thick AGNs. Compton thick (CT) sources with column densities $N_h > 10^{24}$ are difficult to observe in X-rays and the known objects are detected at relatively low redshifts\textsuperscript{13}, i.e. $z < 0.05$. Nevertheless CT AGNs are important to study due to their still unknown number and contribution to the cosmic X-ray background\textsuperscript{12,14}.

In particular, we show a simulation of SXI+HET observation for the source NGC 4945, having a BAT measured flux of $\sim 3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (15-200 keV). A source with same spectrum and flux divided by 50 can be detected by SXI and its spectrum resolved into components.

4.2 Studies of variability and SED of Blazars

In the study of blazars are recognized as very important the characterization of their spectral energy density (SED) and the monitoring of their variability. Blazars have relativistic jets pointing at us. The SED of blazars from radio to $\gamma$-rays is characterized by two broad peaks ascribed mainly to synchrotron and Inverse Compton emission (see Figure 5, left panel, for an example SED\textsuperscript{15}). Depending on the location of the two peaks, they can be classified as belonging to the Low-, Intermediate- of High-Energy peaked class. The X-ray band can often fall into either the high energy tail of the synchrotron peak or the low energy tail of the IC peak, with very different spectral slopes. For objects with insufficient multiwavelength coverage, X-ray spectra from 0.1 to 100 keV as could be provided by SXI and HET can be sufficient to constrain or classify them as belonging to either classes. Furthermore as the SED can be variable, X-ray spectra slopes can provide constraints on its shape throughout very long, continuous time span.
Figure 6. Simulated spectrum of a bright burst spectrum as seen by SXI with absorption edges. See text for details.

An example of variability studied in multifrequency is reported in Figure 5, right panel for PKS 2155-304. For this source the large variability detected in $\gamma$-rays, but not in optical/X-ray suggests probably two SED emitting zones, of which only one is responsible for the flaring emission\textsuperscript{16}.

Therefore the study of the variability of Blazars is a clue to unveil the properties of the emission region. Multiwavelength coverage with time as could be provided by EXIST, each time a blazar will be pointed and fast follow-up of flares will be invaluable to test models.

4.3 Investigations of GRB early spectra and afterglows

Swift/XRT observations have raised a lot of new issues about the origin of the emission mechanisms for the prompt and late (afterglow) emission in GRBs. Since many GRB afterglows could be emitted by an ISM environment, a sensitive measurement of the X-ray afterglow and detection of features in the early afterglow emission could help to unveil the structure of the medium surrounding the central engine. In particular, the X-ray emission can be used as a tool to investigate the properties of the circumburst medium which imprints characteristic absorption edges on the X-ray spectrum through which element abundances can be computed, and some constraints on the evolution of the progenitor can be set.

This "edge diagnostics" has been applied for one of the closest GRBs observed by Swift, GRB 060218, leaving to the conclusion that low Z metals have been ejected from the progenitor before collapse\textsuperscript{17}. A good energy resolution as provided by EXIST/SXI could provide the tool to study the absorption edges formed in the circumburst environment for a number of GRBs. The estimates of the edges could also serve as an estimate to GRB redshift. In Figure 6 we show a simulation of a bright GRB (flux: $10^{-9}$ cgs for 1ks) obtained on the basis of the model used for GRB 060218\textsuperscript{17}. Many of the absorption edges from the model are clearly resolved. The simulations also show that for a typical faint XRT burst (a factor 10 lower in intensity) it is still possible to obtain measurements of the redshift within an error as low as $\sim 6\%$.

5. CONCLUSIONS

The SXI telescope on board EXIST will take full advantage of the operational strategy adopted for the mission, mostly based on surveys and fast follow-up of GRB and transients. With SXI, EXIST is a real multiband observatory with a sensitive broadband coverage at high energies: 0.1-600 keV, with SXI providing an effective area of 950cm$^2$ at 1.5keV. SXI will perform wide area surveys (scanning & serendipitous) and sensitive observation of transient events in the X-ray (e.g. GRB afterglows, AGN flares). It will also help the identification of HET
sources detected during the survey, study the absorbed (even Compton thick) AGN Universe and zoom on AGN states.

The heritage of the Swift/XRT, XMM-Newton and INTEGRAL allows to conclude that the SXI performance is appropriate to the profile of the EXIST mission as currently designed. Main improvements to Swift/XRT are: factor $\sim 10$ effective area, fast detector readout allowing operation during scanning survey.

ACKNOWLEDGMENTS

The Italian authors acknowledge the support of ASI contract I/088/06/0.

6. REFERENCES

1. N. Gehrels, G Chincarini, P. Giommi, K. O. Mason, J. A. Nousek, A. A. Wells, N. E. White, S. D. Barthelmy, D. N. Burrows, L. R. Cominsky, K. C. Hurley, F. E. Marshall, P. Meszaros, P. W. A. Roming, "The Swift Gamma-Ray Burst Mission", ApJ 611, p. 1005, 2004

2. F. Jansen, D. Lumb, B. Altieri, J. Clavel, M. Ehle, C. Erd, C. Gabriel, M. Guainazzi, P. Gondoin, R. Much, R. Munoz, M. Santos, N. Schartel, D. Texier, G. Vacanti, "XMM-Newton Observatory. I. The spacecraft and operations", A&A 365, p.L1-L6, 2001

3. C. Winkler, T. J.-L. Courvoisier, G. Di Cocco, N. Gehrels, A. Gimnez, S. Grebenev, W. Hermsen, J. M. Mas-Hesse, F. Lebrun, N. Lund, G. G. C. Palumbo, J. Paul, J.-P. Roques, H. Schnopper, V. Schnfelder, R. Sunyaev, B. Teegarden, P. Ubertini, G. Vedrenne and A. J. Dean, "The INTEGRAL mission", A&A 411, L131, 2003

4. D. N. Burrows, J. E. Hill, J. A. Nousek, J. A. Kennea, A. Wells, J. P. Osborne, A. F. Abbey, A. Beardmore, K. Mukerjee, A. D. T. Short, G. Chincarini, S. Campa, O. Citterio, A. Moretti, C. Panagia, G. Tagliaferri, P. Giommi, M. Capalbi, F. Tamburelli, L. Angelini, G. Cusumano, H. W. Brauninger, W. Burkert and A. D. Hartner, "The SWIFT X-ray telescope" Space Sci. Rev., 120, 165, 2005

5. P. Ubertini, F. Lebrun, G. Di Cocco, A. Bazzano, A. J. Bird, K. Broenstad, A. Goldwurm, G. La Rosa, C. Labanti, P. Laurent, I. F. Mirabel, E. M. Quadrini, B. Ramsey, V. Reglero, L. Sabau, B. Sacco, R. Stauber, L. Vigroux, M. C. Weisskopf and A. A. Zdziarski, "IBIS: the Imager on board INTEGRAL", A&A 411, L141, 2003

6. A. J. Bird, A. Malizia, A. Bazzano, E. J. Barlow, L. Bassani, A. B. Hill, G. Belanger, F. Capitano, D. J. Clark, A. J. Dean, M. Fiocchi, D. Gotz, F. Lebrun, M. Molina, N. Produit, M. Renaud, V. Sguera, J. B. Stephen, R. Terrier, P. Ubertini, R. Walter, C. Winkler, J. Zurita, "The 3rd IBIS/ISGRI soft gamma-ray survey catalog", ApJ.SuppL, 170, 175, 2007

7. J. E. Grindlay, the EXIST Team, "GRB Probes of the High-Z Universe with EXIST", AIPC, Vol. 1133, p.18, 2008

8. J. Hong et al., these Proceedings, 2009

9. A. Kutirev et al., Proc. SPIE Conf. 7453, 2009 (in press)

10. G. Tagliaferri et al., Proc. SPIE Conf. 7437, 2009 (in press)

11. M. G. Watson, A. C. Schroder, D. Fyfe et al., "The XMM-Newton serendipitous Survey. V. The Second XMM-Newton Serendipitous Source Catalogue", A&A 493, 339, 2009

12. A. Malizia, J. B. Stephen, L. Bassani, A. J. Bird, F. Panessa, P. Ubertini, "The fraction of Compton-thick sources in an INTEGRAL complete AGN sample" MNRAS, in press, 2009 (arXiv 0906.5544)

13. R. della Ceca, P. Severgnini, A. Caccianiga, A. Comastri, R. Gilli, F. Fiore, E. Piconcelli, G. Malaguti and C. Vignali, "Heavily obscured AGN with BeppoSAX, INTEGRAL, Swift, XMM and Chandra: prospects for Simbol-X", Mem. SAIt Vol.79, p.65, 2008
14. E. Treister, C. M. Urry, S. Virani "The Space Density of Compton-Thick Active Galactic Nucleus and the X-Ray Background" ApJ 696, 110, 2009

15. S. Watanabe, R. Sato, T. Takahashi, J. Kataoka, G. Madejski, M. Sikora, F. Tavecchio, R. Sambruna, R. Romani, P. G. Edwards and T. Pursimo, "Suzaku Observations of the Extreme MeV Blazar SWIFT J0746.3+2548", ApJ 694, 294, 2009

16. L. Costamante, "Blazar properties: an Update from Recent Results", Proceedings of the Workshop "High-Energy Gamma-rays and Neutrinos from Extra-Galactic Sources", January 13-16, 2009, to be published in Int. J. Mod. Phys. D, 2009 (arXiv 0907.3967)

17. S. Campana, N. Panagia, D. Lazzati, A. P. Beardmore, G. Cusumano, O. Godet, G. Chincarini, S. Covino, M. Della Valle, C. Guidorzi, D. Malesani, A. Moretti, R. Perna, P. Romano, and G. Tagliaferri, "Outliers from the Mainstream: How a Massive Star Can Produce a Gamma-Ray Burst", ApJ 683, L9, 2008