

An overview of the EXTraS project: Exploring the X-ray Transient and Variable Sky

A. De Luca^{*a†}, R. Salvaterra^a, A. Tiengo^b, D. D'Agostino^c, M.G. Watson^d, F. Haberl^e and J. Wilms^f on behalf of the EXTraS collaboration

^aINAF-Istituto di Astrofisica Spaziale e Fisica Cosmica di Milano (IASF)
Via Bassini 15, 20133 Milano, Italy

^bIstituto Universitario di Studi Superiori di Pavia (IUSS)
Piazza della Vittoria 15, I-27100 Pavia, Italy

^cCNR-Istituto di Matematica Applicata e Tecnologie Informatiche (IMATI)
Via de Marini 6, I-16149 Genova, Italy

^dUniversity of Leicester, Department of Physics and Astronomy
Leicester, LE1 7RH, UK

^eMPG-Max Planck Institut für extraterrestrische Physik
Giessenbachstrasse, D-85748 Garching, Germany

^fErlangen Center for Astroparticle Physics (ECAP)
Sternwartstrasse 7, D-96049 Bamberg, Germany

E-mail: deluca@iasf-milano.inaf.it, ruben@iasf-milano.inaf.it,
andrea.tiengo@iusspavia.it, dagostino@ge.imati.cnr.it,
mgw@leicester.ac.uk, fwh@mpe.mpg.de,
joern.wilms@sternwarte.uni-erlangen.de

The EXTraS project (“Exploring the X-ray Transient and variable Sky”) will harvest the hitherto unexplored temporal domain information buried in the serendipitous data collected by the European Photon Imaging Camera (EPIC) instrument onboard the ESA XMM-Newton X-ray observatory since its launch. This will include a search for fast transients, as well as a search and characterization of variability (both periodic and aperiodic) in hundreds of thousands of sources spanning more than nine orders of magnitude in time scale and six orders of magnitude in flux. X-ray results will be complemented by multiwavelength characterization of new discoveries. Phenomenological classification of variable sources will also be performed. All our results will be made available to the community. A didactic program in selected High Schools in Italy, Germany and the UK will also be implemented. The EXTraS project (2014-2016), funded within the EU/FP7 framework, is carried out by a collaboration including INAF (Italy), IUSS (Italy), CNR/IMATI (Italy), University of Leicester (UK), MPE (Germany) and ECAP (Germany).

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*Speaker.

†Primary coordinator of EXTraS

1. Variability, serendipity and XMM-Newton/EPIC data.

Almost all astrophysical objects, from nearby stars to supermassive black holes at cosmological distances, display a characteristic variability in flux and spectral shape on a broad range of time scales. This is especially true in the high energy range of the electromagnetic spectrum. Study of such variability can yield crucial clues to the nature of the sources and to their emission physics – from magnetic reconnection in stellar atmospheres to accretion on compact objects.

In the soft X-ray energy range (0.1-10 keV), focusing telescopes collect each day a very large amount of information about serendipitous sources and their time variability – each detected photon is time-tagged! – but such information remains mostly unused in data archives. This is the case for the European Photon Imaging Camera (EPIC) instrument onboard the ESA XMM-Newton X-ray observatory. EPIC consists of a pn [1] and of two MOS cameras [2]. Thanks to its unprecedented combination of large sensitivity to point sources, large field of view, good angular, spectral and temporal resolution, EPIC is the most powerful tool to study the variability of faint X-ray sources. Launched in 1999 and still fully operative, EPIC collected more than 230 millions of seconds of data so far (with the prospects for several more years of observations). Large efforts are ongoing to study the serendipitous content of the EPIC database.

- **The XMM-Newton Serendipitous Source Catalogue.** A catalogue of all the X-ray sources detected in EPIC pointed observations is periodically released by the XMM-Newton Survey Science Centre consortium¹. The most recent release, called 3XMM [3] is the richest source catalogue in the soft X-ray range ever compiled, including more than 565,000 detections of about 400,000 unique sources on > 877 square degrees of the sky (more than 70,000 sources have multiple-epoch detections due to the overlap of different observations). Light curves with uniform time bins were extracted for about 133,000 bright sources and basic variability tests were performed.
- **The XMM Slew Survey.** Data collected while the telescopes move from one target to the next scheduled one – the so-called slews – are also a very rich resource. Even if exposure time is short (7-10 s per source), slews are as sensitive as the ROSAT All Sky Survey (RASS) below 2 keV, and have an unrivalled sensitivity above 2 keV, if compared to any currently available all-sky survey. The XMM Slew Survey (XSS) Catalogue [4, 5], generated using EPIC/pn slew data, in its most recent release lists more than 20,000 detections² and covers more than 60% of the sky, about 20% having been scanned more than one time. Although thousands of sources prove to be variable when compared to the RASS, no systematic study of variability has ever been carried out.

In spite of such large efforts, temporal domain information in EPIC serendipitous data remained mostly unexplored so far. The EXTraS project will fill the gap, as a service for the astrophysical community.

¹<http://xmssc.irap.omp.eu/>

²http://xmm.esac.esa.int/external/xmm_products/slew_survey/xmms11d_ug.shtml

2. A time-domain treasure hunt in EPIC data.

EXTraS – Exploring the **X**-ray **T**ransient and variable **S**ky – aims at fully exploring and disclosing the serendipitous content of the EPIC database in the temporal domain and to make it available and easy to use to the whole community. EXTraS starts from (and partially builds upon) the work that led to the release of the XMM serendipitous source catalogue and of the XMM Slew Survey catalogue.

Figure 1 shows the time scale vs. count-rate plane and the region accessible thanks to 3XMM products. EXTraS will systematically extend such region. First, we will study the variability of many more sources. Second, we will go on much shorter time scales – by construction, in 3XMM a source with a count rate of 0.01 cts/s cannot be studied at temporal scales below 2000 s (see Fig. 1). Third, EXTraS will explore for the first time variability on longer time scales, beyond the duration of pointed observations. Fourth, we will also search for periodicities. Different lines of analysis are being implemented in the project.

- **A systematic study of aperiodic, short-term variability** – EXTraS aims at characterizing the bulk of 3XMM sources (possibly about 300,000 sources) on all possible time scales, from the duration of an observation to the instrument time resolution (typically 73 ms and 2.6 s for the pn and MOS cameras). The very broad range of count rates and observing conditions in 3XMM, together with the wide diversity of aperiodic phenomena to be characterized require the use of different techniques to extract all available information. Different approaches are being implemented and tested, to generate, e.g., power spectra based on Fourier analysis, or optimally-binned light curves based on Bayesian Blocks analysis. A whole set of synthetic parameters are then extracted for each source in order to quantify and characterize different manifestations of variability. The challenge is to properly account for several sources of systematics, ranging from gaps in the time series data, to the highly variable EPIC particle background, to the superimposition of the signal of different sources.
- **A systematic search for periodicity.** Such a kind of search had never been performed before on the EPIC database. Different algorithms will be applied to photons' times of arrival, in order to search for pulsations down to $P \sim 0.2$ s in the largest possible number of 3XMM sources (about 300,000). We will use a generalization of the FFT technique accounting for non-poissonian noise components, as well as other techniques such as e.g. the Rayleigh test. A characterization of the signal of all candidate pulsators will be provided. It is also planned to compute upper limits to the pulsed fraction of all analysed sources.
- **A blind search for transient sources.** This will allow to discover a potentially large number of sources that rose above the detection threshold for just a small interval of time. Short transients with a low fluence would easily be missed, confused in the background, in any standard analysis carried out on the time scale of the whole observation. This is the case for the analysis used to produce the serendipitous source catalogue – thus, such transients would not appear in 3XMM. Searches for transients of any duration (possibly down to a few seconds) will be performed within EXTraS, e.g. using a Bayesian Blocks analysis to optimally select promising time intervals for transient source detection. A thorough temporal

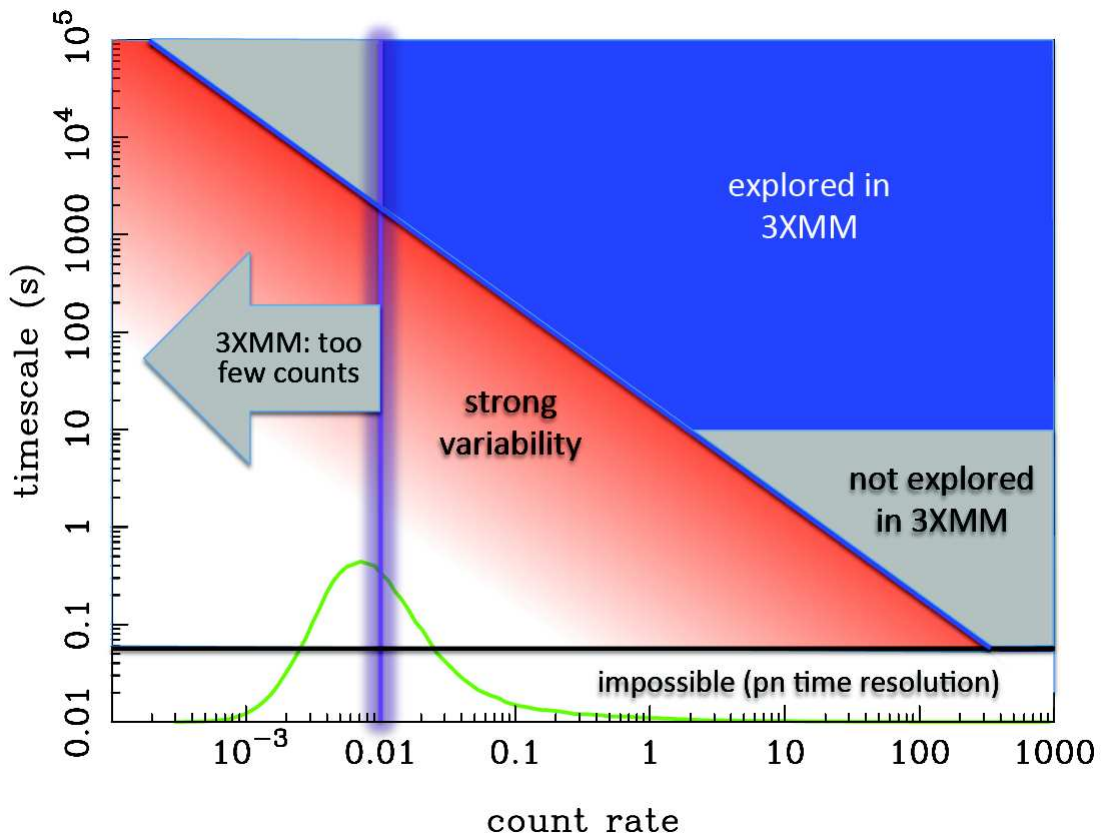


Figure 1: Timescale – count rate parameter space. The blue area marks the region where 3XMM light curves with a uniform time-binning have been extracted. The area is limited by the prescription used to produce such light curves: (i) the diagonal line to the lower left marks the minimum of 20 counts per time bin adopted in 3XMM; (ii) the vertical violet line to the left indicates the approximate source count limit for 3XMM light curve creation; (iii) the horizontal line marks the minimum time bin of 10 s in 3XMM light curves. The green curve superimposed to the diagram shows the distribution of EPIC count rates for 3XMM sources.

study, down to the instrument time resolution, will be carried out for each candidate transient, together with a spectral characterization. This will also include a search for multiwavelength counterparts, mainly based on existing databases.

- **A systematic investigation of long-term variability.** EXTraS will take advantage of the large number of overlapping observations performed at different epochs. Although at lower sensitivity, information will also be extracted on the large fraction of the sky visited by multiple slews. For each 3XMM and XSS source, all count rate measurements at different epochs will be complemented by upper limits computed in case of non-detections in spatially overlapping observations, to produce long-term light curves. This will allow to search for – and characterize – variability on a huge number of sources on time scales up to more than a decade.

Phenomenological classification of all variable sources will also be performed by EXTraS, as an important objective of the project. We will use an automated statistical classification approach,

based on a full set of source “features”, describing all X-ray temporal and spectral properties, as well as on all available information in multiwavelength catalogues and databases. We will test different classification algorithms, starting from results and lessons learned in ongoing efforts related to large optical surveys.

3. The EXTraS output for the community.

All EXTraS results and products, together with new software tools, will be released to the community at the end of the project (end of 2016). Quality control will be a crucial task within EXTraS. A careful screening and validation process will be carried out to reject possibly flawed results and products generated by our automatic pipelines. A repository will be deployed, with an easy-to-use, Virtual Observatory-compliant web interface. Highly customizable interrogations will be possible for all users, even if they have no previous experience with X-ray data.

The EXTraS database will include a full characterization of the temporal behaviour of hundreds of thousands of sources, spanning more than nine orders of magnitude in time scale (from <1 s to >10 yr) and six orders of magnitude in flux (from $\sim 10^{-9}$ to $\sim 10^{-15}$ erg cm $^{-2}$ s $^{-1}$ in 0.2-12 keV). We trust this will be a very rich and useful resource for the community, with a direct relevance for a very broad range of topics in almost all fields of astrophysics – from strong gravity, to accretion-related phenomena, to magnetic field generation and dynamics, to the solar-stellar connection and the habitability of planetary systems. Very different ways of exploitation can be expected as well, from the study of specific variable sources, to population studies of different source classes, to the search for rare events, to the selection of extreme objects. Totally unexpected discoveries can also be foreseen, as has always been the case when new regions in parameter space have been explored. A concise overview of possible science cases that could benefit from EXTraS results is given by [6].

4. Education with EXTraS

We will also implement an experimental didactic program in High Schools in Italy, Germany and the UK, directly involving students in the project activities. After a series of introductory lessons, students will have access to a selected sample of EXTraS results. Using our visualisation tools, they will be asked to classify sources according to their phenomenological affinity to a set of templates. Results provided by students will be compared to results provided by astronomers of the EXTraS team as well as to the output of our automated classification algorithms. Thus, our educational activity will turn also to an experiment of citizen science, allowing us to assess the viability of involving non-expert (but trained) people in a complex classification task.

5. The EXTraS consortium.

The EXTraS project is carried out by an international collaboration featuring:

- National Institute for Astrophysics (INAF, Italy), coordinating the EXTraS consortium, participating mainly with the Istituto di Astrofisica Spaziale e Fisica Cosmica (IASF Milano)

and with the astronomical observatories of Roma (OA-Roma), Brera (OA-Brera), Catania (OA-Catania) and Trieste (OA-Trieste).

- Istituto Universitario di Studi Superiori di Pavia (IUSS, Italy);
- National Council for Research (CNR, Italy), participating with the Institute of Applied Mathematics and Information Technologies (IMATI);
- University of Leicester (United Kingdom);
- Max Planck Society for the Advancement of Science (MPG, Germany), participating with the Max Planck Institute for Extraterrestrial Physics (MPE);
- Friedrich-Alexander Universitat Erlangen-Nuremberg (Germany), participating with the Erlangen Centre for Astroparticle Physics (ECAP).

For more information, updates on the status of the project, and a full list of contacts, please refer to the EXTraS website, online at www.extras-fp7.eu.

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