Exploring the X-ray Transient and Variable Sky

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on behalf of the EXTraS collaboration

University of Hong Kong - July 4th 2016
outline

• XMM and its sources
• The EXTraS project
• 4 different kinds of variability
• 3 innovative techniques
• 3 scientific cases
• Outreach & media coverage
• The EXTraS legacy
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XMM and its sources

- Photons of energy 0.1-100 keV
- Atmosphere absorbs X-rays
- X-ray astronomy born in 1962
- Thermal and non-processes
- Variety of point-like emitters: mainly stars & compact objects
- Variety of extended sources: SNR, PWN, galaxy clusters
atmospheric absorption

X-rays
M31: the Andromeda galaxy

Optical

Infrared

X-rays

credit: R.Gendler

HERSCHEL

XMM-Newton
XMM and its sources

- **XMM-Newton**: ESA, Dec 1999
- **L10.8m x W16.2 m ~ 3.8 Tons**
- **30+130 ks eccentric orbit**
- **EPIC (2MOS+PN) + 2RGS + OM**
X-ray Optics
XMM and its sources

- 3 co-aligned mirrors & filters
- independent cameras & modes
- Field of view: rad ~15 arcmin
- PN camera = 1 x 12 CCDs
- PN: high Aeff and Tres<74ms
- MOS cameras = 2 x 7 CCDs
- MOS: loose Aeff for RGS
- MOS: Tres 2.6s for 6 CCDs
European Photon Imaging Camera
EPIC effective Area

![Graph showing effective area vs energy for different detectors and orders](image)
PN operating modes

- Full Frame: 73.4ms
- Large Window: 47.7ms
- Small Window: 5.7ms
- Timing: 0.03ms
MOS operating modes

Full Frame

Large Window

Small Window

Timing

2.6s

2.6s

2.6s

.9s

1.75ms

.3s
XMM and its sources

- 3XMM-DR4 catalog (up to 2012)
  Rosen et al. 2015
- >2e8s of pointed observations
- covers ~800 square degrees
- contains 550,000 detections
- DR5 (& DR6) released
- the largest X-ray source catalog
XMM and its sources

• XMMSL1: XMM slew survey catalog
  Saxton et al, 2008
• XSS: slew survey catalog 2-12keV
  Warwick Saxton & Read, 2012
• observation taken between pointings
• contains >20,000 sources
• covers a good fraction of the sky
## Statistics of the XMM-Newton catalogues

<table>
<thead>
<tr>
<th></th>
<th>3XMM-DR4</th>
<th>Cleaned Slew Survey (xmms1D6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of detections</td>
<td>531261</td>
<td>20163</td>
</tr>
<tr>
<td>Number of unique sources</td>
<td>373728</td>
<td>~18400</td>
</tr>
<tr>
<td>Unique sources with &gt; 1 detection</td>
<td>66728</td>
<td>&gt; 950</td>
</tr>
<tr>
<td></td>
<td>(up to 44 repeats)</td>
<td>(up to 8 repeats)</td>
</tr>
<tr>
<td>Non overlapping sky coverage</td>
<td>1.9%</td>
<td>~68%</td>
</tr>
</tbody>
</table>

*The slew survey catalogue will be improved and augmented as part of the EXTraS project.*

credit: S. Rosen
XMM and its sources

- Data are proprietary only for 1yr
- Public data can be retrieved from several astronomical databases (LEDAS, XSA, HEASARC)
- Public software (SAS) and user support for data analysis
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The EXTraS project - 1

- EU-funded project (FP7)
- PI: Andrea De Luca (INAF-IASF)
- 3 years: 2014 - 2016
- 3 countries (Italy-Germany-UK)
- 6 partner institutions: INAF (IT) + IUSS (IT) + CNR (IT) + MPE (DE) + FAU (DE) + ULEIC (UK)
- 9 work packages
Exploring the X-ray Transient and variable Sky

Home

Exploring Hidden Treasures

"Variability pervades the cosmos. Studies of variability dominate research in astronomy and astrophysics and are so common that very many groups, projects and instruments are dedicated to the examination of just one form of variability, or one aspect of its diverse manifestations." (manifest of the IAU Symposium 285, "New Horizons in Time Domain Astronomy", University of Oxford September 19-23, 2011)

News:

EXTras Workshop
EXTras announces an upcoming workshop to be held in Pavia (Italy) on November 21-23, 2016. The workshop is devoted to...

EXTras HEASARC PoW
NASA has chosen EXTras for High Energy Astrophysics Picture of the Week (PoW) to celebrate the upcoming workshop...
The EXTraS project - 2

Main Goal:

“Characterise as well as possible the variability of XMM sources in public archives, by providing tools and a catalogue to the community”

Keywords:

Variability - Serendipity - XMM
The EXTraS project - 5
The EXTraS project - 6

1. Coordination (INAF)

2. **Aperiodic variability (INAF)**

3. Periodic variability (INAF)

4. Search for transients (IUSS)

5. Long-term variability (ULEIC)

6. Validation & screening (MPE)

7. MWL & classification (MPE & FAU)

8. Archival and computing (CNR & ULEIC)

9. Outreach and dissemination (INAF)
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4 different kinds of variability

- characterisation of aperiodic variability
- nearly all 3XMM sources
- uniform & adaptive bin light curves + FFTs
- synthetic parameters describing variability

credit: D. Salvetti
4 different kinds of variability

- search for periodicity in nearly all 3XMM sources
- unbinned, single cameras or combined DFTs
- Z2 and red-noise correction (Israel & Stella 1996)
- period or upper limits on the pulsed fraction
4 different kinds of variability

- search for transients in all XMM observations
- uniform and adaptive slicing and detections
- full X-ray and MWL characterisation
4 different kinds of variability

- characterisation of long term variability
- merge of 3XMM and XSS catalogs
- long term light curves, including upper limits
- model fitting and extraction of parameters

credit: A. Read
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3 innovative techniques - 1a

- EPIC cameras suffer from 2 kinds of background contamination
  - Photons + HECRs ~ stable, weak
  - Soft protons ~ highly variable, strong
- Standard analysis recommends to discard all times of background flares
  - This excludes >1/3 of the EPIC time
- Within EXTraS we keep all data
3 innovative techniques - 1b

• Our strategy (Martino Marelli) is to separate the two components
• Each one has a different vignetting that we assume doesn’t change with time
• We use advanced techniques for fitting the morphology of background maps
• We obtain a reliable estimate of the time-dependent background level for each single source
Input 3XMM Background Light Curve

On-flare periods have both the components.

Off-flare periods have only the constant component.

credit: M.Marelli
a typical example
3 innovative techniques - 2a

• Bayesian blocks (Scargle 2012): standard adaptive binning technique
• Basic implementation compares rate levels, assuming constant background
• We must extend the technique to deal with the variable EPIC background
• We also want an intensive threshold, that fixes the probably that any block could be spurious, not a global one
3 innovative techniques - 2b

- Our strategy (David Salvetti) is to marginalise the source rate over the background rate distribution.
- We use as a fitness function the logLike distribution of the source rate.
- We set an intensive threshold of 3 sigma, for separating 2 blocks.
- We compute a number of statistical parameters to describe the light curve.
some statistics for ~780,000 X-ray light curves
3 innovative techniques - 3a

• Most 3XMM sources have very few counts, in particular when binned

• The standard tools for estimating the signal subtracting the background assume Gaussian statistics or known background level

• We need to extract the net signal from a measure contaminated by background when both are in the Poisson regime
3 innovative techniques - 3b

• We marginalise the signal over 1 or more background components, imposing only non-negative values for signal and bkg

• We can reduce the problem to the estimate of the net signal, from a pair of measures, On and Off source.

\[
\text{On} = s + f
\]
3 innovative techniques - 3c

$On = S + f$

$N_{On} \sim \text{Poiss}(\mu_{On}) = \text{Poiss}(\mu_s + \mu_f)$

$Off = z \cdot f$

$N_{Off} \sim \text{Poiss}(\mu_{Off}) = \text{Poiss}(z \cdot \mu_f)$
3 innovative techniques - 3d

• how do we estimate the significance of a signal?
• start from a Null Hypothesis of background only
• the problem has an exact solution: it becomes a binomial partition [Przyborowski & Wilenski, 1940]:

\[
p-val = \frac{(n_{on} + n_{off})!}{(z + 1)^{n_{on} + n_{off}}} \times \sum_{n=n_{on}}^{n_{on}+n_{off}} \frac{z^{n_{on} + n_{off} - n}}{n! \times (n_{on} + n_{off} - n)!}
\]

• with a very small p-val we can reject the NH
3 innovative techniques - 3e

- how do we estimate the posterior distribution of a signal?
- start from Poisson Likelihood profiles

\[ \mathcal{L}(\mu_s, \mu_f | n_{on}) = e^{-(\mu_s + \mu_f)} (\mu_s + \mu_f)^{n_{on}} \]

\[ \mathcal{L}(\mu_f | n_{off}) = e^{-\mu_f} (\mu_f)^{n_{off}} \]

- then marginalise over the background

\[ \mathcal{L}(\mu_s | n_{on}, n_{off}) = \int_0^{+\infty} \mathcal{L}(\mu_s, \mu_f | n_{on}) \times \mathcal{L}(\mu_f | n_{off}) \, d\mu_f \]
3 innovative techniques - 3f

- and here is the result:

\[
\mathcal{L}(\mu_s | n_{on}, n_{off}) = \frac{e^{-\mu_s}}{K} \times \sum_{j=0}^{n_{on}} C_j(n_{on}, n_{off}) \times \mu_s^j
\]

\[
C_j(n_{on}, n_{off}) = \frac{(z + 1)^j \times (n_{on} + n_{off} - j)!}{(n_{on} - j)! \times j!}
\]

\[
K = (z + 1)^{n_{on}} \times \sum_{j=0}^{n_{on}} \frac{(n_{off} + j)!}{j! \times (z + 1)^j}
\]
3 innovative techniques - 3g

```python
In [1]: from BLike import BLike

In [2]: L=BLike(N_on=23, N_off=20, bkg_ratio=2.)

In [3]: print 'Detection at %.2f sigma (P-value=%.2e)' % (L.Significance(), L.Significance(True))
   Detection at 2.80 sigma (P-value=5.07e-03)

In [4]: print 'Best fit %.3f +/-%.3f -%.3f' % (L.MostLikely(), L.ErrorBar(), L.ErrorBar(False))
   Best fit 12.770 +5.249 -5.404

In [5]: import matplotlib.pyplot as plt

In [6]: import numpy as np

In [7]: X=np.arange(0., 30., .01)

In [8]: Y=[L.Get(x) for x in X]

In [9]: A=plt.plot(X, Y)

In [10]: plt.show()
```
In [11]: L.Integrate(15, 25)
Out[11]: 0.3518258952415475

In [12]: L.UpperLimit()
Out[12]: 23.07889473438263

In [13]: L.GetIntegral(_)
Out[13]: 0.95450034035389952

In [14]: L.UpperLimit(coverage=.99)
Out[14]: 27.220936238765717

In [15]: L.MostLikely()
Out[15]: 12.769500732421875

In [16]: L.Integrate(_ - L.ErrorBar(up=False), _ + L.ErrorBar(up=True))
Out[16]: 0.68268948135806107

In [17]: L.MaxLike()
Out[17]: 0.075207812762068615

In [18]: L.Get(12.37)
Out[18]: 0.074989870469523739

In [19]: L.TS(12.37)
Out[19]: 5.1808044699473079
3 innovative techniques - 3h
Background subtracted time series  Mean Rate= $8.98929 \times 10^{-3}$

Counts/sec

Time (secs)

Background time series  Mean Rate= $5.27787 \times 10^{-3}$

Counts/sec

Time (secs)
$-2 \times \Delta \log \text{like} \sim \chi^2_{1 \, \text{dof}}$

Expected Background Subtracted Count Rate (cts/s)
\[ \rho_S = 7.68^{+1.03}_{-0.97} \times 10^{-3} \text{ cts/s} \]
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3 scientific cases - 1

- Known object in rho Ophiuchi SFR
- Flare from a YSO of class 0/I (extremely rare)
- Pizzocaro et al. 2015
3 scientific cases - 2

**Swift J0045.2+4151: analysis of XMM-Newton archival data**

ATel #7181; A. Belfiore (INAF/IASF Milano), A. Tiengo (IUSS Pavia), G. L. Israel (INAF/OA Roma), A. M. Read (U. Leicester), R. Salvaterra, D. Salvetti (INAF/IASF Milano), G. Novara (IUSS Pavia), S. Mereghetti, M. Marelli (INAF/IASF Milano), G. Rodríguez (INAF/OA Roma), G. Lisini (IUSS Pavia), S. R. Rosen (U. Leicester), A. De Luca (INAF/IASF Milano)

on 6 Mar 2015; 15:49 UT

Credential Certification: Sandro Mereghetti (sandro@mi.iASF.cnr.it)

Subjects: X-ray, Gamma-Ray Burst, Soft Gamma-ray Repeater, Transient

Referred to by ATel #: 7185, 7187

Based on the preliminary results of the EXTras project (DeLuca et al. 2015, arXiv:1503.01497), we report on the analysis of XMM-Newton archival data of XMM J0045.2+4151 (aka 1PFH2005)

- fast response to an ATel (within 2 days)
- typical use of EXTrasS results
• An accreting 1.2s pulsar in a 1.27d orbit
• The first pulsar found in the Andromeda galaxy
• Esposito et al. 2016
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Outreach & media coverage

Competition in the Brera fine arts academy for the EXTraS logo

The EXTraS newsletter

credit: S. Sandrelli

credit: F. Canaparo

credit: S. Sandrelli

EXTraS in a nutshell

We will characterise the temporal behavior of the largest ever sample of objects in the soft X-ray range with a complex, systematic and consistent analysis of the whole XMM-Newton/EPIC database. We will release a public catalogue including all products and results of our analysis, together with visualisation tools. This will serve a very broad community, helping to address a wide range of unsolved problems in almost all fields of astrophysics. EXTraS has received funding from the European Union’s Seventh Framework Programme under the Space-2011-1 Call.

EXTraS Start date: 01 Jan 2014
Duration: 36 months
Involves countries: Italy, UK, Germany
Involves institutes: INAF (coordinator), CNR (ISDC, University of Leicester, LAM, MPI, FAU (D))
Project coordinator: A. De Luca
Web: www.extras-tp7.eu

Science with EXTraS

Our project will allow for a significant step forward in our characterization and understanding of variable X-ray phenomena timescales ranging from $10^{-1}$ to $10^{10}$ years, and on flux ranges spanning from $10^{-9}$ to $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in the 0.2-10 keV energy range. The extremely large range of variability timescales and fluxes allows to investigate a wide diversity of astrophysical phenomena from Galactic objects to the most distant cosmological events (see figure 1).

Without demanding completeness, some of the most interesting variable sources that are expected to be studied within the EXTraS project are:

- Fast stars
- Stellar flares are the result of the energy release in magnetic reconnection. Hundreds of bursts are expected from a broad population of stars and prestars (YSOs).
Workshops with high-school students
**FOUND: ANDROMEDA'S FIRST SPINNING NEUTRON STAR**

31 March 2016

Decades of searching in the Milky Way's nearby 'twin' galaxy Andromeda have finally paid off, with the discovery of an elusive breed of stellar corpse, a neutron star, by ESA's XMM-Newton space telescope.

Andromeda, or M31, is a popular target among astronomers. Under clear, dark skies it is even visible to the naked eye. Its proximity and similarity in structure to our own spiral galaxy, the Milky Way, make it an important natural laboratory for astronomers. It has been extensively studied for decades by telescopes covering the whole electromagnetic spectrum.

Despite being extremely well studied, one particular class of object had never been detected: spinning neutron stars.

Neutron stars are the small and extraordinarily dense remains of a once-massive star that exploded as a powerful supernova at the end of its natural life. They often spin very rapidly and can sweep regular pulses of radiation towards Earth, like a lighthouse beacon appearing to flash on and off as it rotates.

These 'pulsars' can be found in stellar couples, with the neutron star cannibalising its neighbour. This can lead to the neutron star spinning faster, and to pulses of high-energy X-rays from hot gas being funnelled down magnetic fields on to the neutron star.

Binary systems hosting a neutron star like this are quite common in our own Galaxy, but regular signals

Andromeda's pulsing neutron star.

EXTraS! EXTraS! X-ray Pulsar Discovered in M31!

Neutron stars are the incredibly dense bits of the core of an exploded high-mass star. Neutron stars are as massive as the Sun, yet small enough to fit inside the Washington DC beltway. X-ray pulsars are spinning neutron stars that accrete material from a companion star. As the material falls towards the neutron star, its unbelievably strong gravity heats the material to temperatures of millions of degrees at localized spots near the neutron star. As
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- Aperiodic variability
- Periodicity search
- Transient search
- Long-term variability

EPIC data analysis

Phenomenological classification
- Automatic algorithm, using all src properties
- MWL characteriz.
  - For new discoveries

Public archive results & products
- SW tools
  - VO tools
  - Release: end of 2016

New science, more science
Increasing the potential for discovery of XMM for the next decade

credit: A. De Luca
The EXTraS legacy

I would need to analyse that XMM dataset...

credit: D. D’Agostino
The EXTraS legacy

• Software tools will soon be released with a detailed documentation
• A full catalog is in preparation
• You will be able to download many products through public archives
• You will be able to run your own analyses through a science portal
• You can use our tools and results for statistical analysis or to study your favourite X-ray source!
EXTraS Science Workshop

Pavia

November 21-23, 2016

variable phenomena in the X-ray Sky:
Stars, INSs, CVs, LMXBs, HMXBs, ULXs, AGN, SNe, TDEs, GRBs
Thanks! That’s all!