Exploring the X-ray Transient and variable Sky

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Outline

A talk about a past project, its outcome (yet to be fully explored) and some recent developments

1. Time domain astronomy, Serendipity, XMM-Newton
2. EXTraS (2014-2016): data analysis and products
   - aperiodic, short-term variability
   - search for periodicity
   - search for new transients
   - long-term variability
3. Recent work
4. Science highlights
Time-domain astronomy

Aperiodic, transient, periodic phenomena in the high-energy sky

AGN  μQSO  TDE  HMXB

AGN  LMXB  SN-SBO  RPPSR

HMXB  GRB  SGR  CV

AXP  Star  LMXB
From variability to physics

Accretion physics
• radiation efficiency of accretion flows
• generation of winds and jets
• role of magnetic field

Strong gravity physics

Mechanisms behind massive stars explosions

Physics of B-field generation and dynamics
• in compact objects
• in normal stars
The EXTraS project (2014-2016)

EXTraS goals:
• extract all temporal domain information from EPIC data;
• characterise it;
• release it to the community in an easy-to-use form.

XMM-Newton/EPIC
Most powerful tool to study variability in faint X-ray sources
Very large and growing archive of serendipitous data
The EXTras project

Funded by EU FP7-Space-2013-1
2014-2016

as a service to the astronomical community

The EXTraS project

Data analysis: 4 pipelines
1. Aperiodic, short-term variability
2. Search for pulsations
3. Search for new, faint transients
4. Long-term variability

Run on all public data available at the time of the project (3XMM-DR4 / DR5)
The EXTraS project

Aperiodic variability

1. Largest possible fraction of sources, down to very faint fluxes;
2. all EPIC data, including time intervals affected by high bkg;
3. variability at the shortest time scales even in faint sources;
4. energy-resolved analysis and spectral variability;
5. full set of quantitative parameters to describe variability

We investigated 300,000 XMM un. sources

- Light curves (uniform time bins; Bayesian blocks) in 4 energy ranges; CDFs
- Hardness ratios;
- FFT spectra;
- Set of temporal features (best fit model parameters; moments of count rate distributions; quantile-based parameters; min/max gradient …)

De Luca+2021, A&A 650, 167
The EXTraS project

Periodicity

1. first systematic search for pulsations in EPIC sources
2. based on unbinned photon TOAs
3. all EPIC data, including time intervals affected by high bkg
4. large fraction of sources in the catalogue

Systematic study of >300,000 sources

- Search based on unbinned photons TOAs
  - FFT-based à la Israel&Stella (1996)
  - taking into account properties of “colored” noise
  - Follow-up of candidates with Rayleigh test

- Period, significance, Folded LCs
- 3.5sigma U.L. on pulsed fraction

De Luca+2021, A&A 650, 167
The EXTraS project

New transients

1. first systematic search on all EPIC data
2. high bkg time intervals included in the analysis
3. transient search at all time scales

Missed by standard source detection
we investigated ~7,800 observations
2 approaches: Bayesian blocks; uniform bins
- Position, temporal properties
- Detection parameters in 3XMM energy bands

Catalogue of 136 “bright” transients

De Luca+2021, A&A 650, 167
The EXTraS project

**Long-term variability**

1. first systematic search on all EPIC data
2. Slew data included in our analysis
3. Larger slew dataset

- long-term LCs based on flux measurements & upper limits for all srcs. using all available data
- Test, quantification, characterization of variability
- Catalogue with 2 million photometric measurements for >400,000 sources

De Luca+2021, A&A 650, 167
(no more) Online resources

EXTraS web site
Based at CNR/IMATI

EXTraS Public Data Archive
Based at Leicester (LEDAS)

EXTraS Science gateway
Based at CNR/IMATI, running on EGI

Security issues after beginning of war
Discontinued because of lack of dedicated manpower
Products and results available

Toulouse, 2024 Feb 27
Recent developments

Limited by shortage of manpower

**Short-term, aperiodic variability**

1. Generation of **EPIC light curves** with uniform time bins combining pn and MOSs

2. Production of smoothed CDFs

3. Characterization of variability based on these new products

**Search for pulsations**

1. Search for accelerated coherent signals

2. Search for coherent signals from binary systems (orbital parameters)

3. Search for pulsations accounting for both orbital and intrinsic Pdot variations

Run on all data collected up to the end of 2022


Run on several $10^4$ LCs

See Israel+2022, MemSAIt 93, 34 and ref. therein
Exploring Machine learning

1) Classification of variability using machine learning (based on temporal features)
   
   a. **Unsupervised classification of all variable sources**
      using Self Organizing Maps
   
   b. **Supervised search for flares**
      XGBoost, NBMs

2) Search for faint transients in photon lists (preliminary)
   
   Using Graph ANN with curriculum training
   Using message passing clustering

Kovacevic+2022, A&A 659, 66
Pasquato+2024, in prep
New online resources

New public data archive based at IASF-Milano – expected release in late spring 2024

Results of updated pipelines

Aperiodic variability: EPIC LCs with 4 uniform time binning; single camera LCs with uniform & adaptive bins; smoothed CDFs; temporal features; flare flag

Complex queries on features

Interactive visualization of products

Download of products and catalogues
Science with EXTraS

X-ray luminosity (erg/s)

Variability timescale (s)

10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}

10^{35} 10^{40} 10^{45}

10 kpc 1 Mpc 1 Gpc 1 Gpc

SGR

GRB afterglow

SN Ibc/II Breakout

TDE

AGN

ULX

X-ray binary

Flare star

Dwarf Nova
**Pulsators:**


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**Aperiodic variability:**

Pulsations in NGC5907 ULX-1

Israel + 2017, Science 355, 817

$L_X \sim 0.15-1.6 \times 10^{41}$ erg/s

brightest PSR ever detected

“local” $P_{\dot{\text{p}}}$: several $-10^{-9}$ s/s

“secular” $P_{\dot{\text{p}}} = -8.1(1) \times 10^{-10}$ s/s

$P/P_{\dot{\text{p}}} \sim 40$ yr !!!

$P_{\text{orb}} = 5.3^{+2.0}_{-0.9}$ days (1)

likelihood analysis (circular orbit)

Dipolar B component

(“Magnetospheric boundary)

$(0.7 – 3.0) \times 10^{12}$ G @ $b \sim 1/10-1/7$

Multipolar B component

(“surface/bottom of the accretion column)

$(3-30) \times 10^{13}$ G
A candidate magnetar in the LMC

Imbrogno+2023, MNRAS 524, 5566

Period search

**Properties**

- **Period (P)**: 7.25s
- **Peak to Faint Ratio (PF)**: 86%
- **X-ray luminosity ($L_x$)**: $2.7 \times 10^{34}$ erg/s
- **Detected in**: 1/6 observations
- **PL spectrum**: $\Gamma = 1.9$

**Possible counterpart**: G8-K3

Properties best described by the magnetar interpretation
An X-ray superflare from a L dwarf located in the core of the CDFS!

VLT/VIMOS Spectrum \(\rightarrow\) L1 ultracool dwarf

The coolest star ever detected in X-rays

\[ E \sim 2 \times 10^{33} \text{ erg} \]

No other flares in 3.5Ms of XMM data

Mechanism to store and release such a dramatic amount of energy in such a tiny star is a mystery

A flare from a very early protostar


Position → CRBR51, a known YSO
Spectrum → highly absorbed stellar flare
IR SED → class 1 YSO!
X-ray emission from such early proto-stars is poorly known
A puzzling flaring source

Selected by a group of High-School students in a stage at INAF/IASF Milano in 2017, September
A puzzling flaring source

Three relatively steady X-ray sources (white circles) were outshone by a mysterious body (yellow arrow) that erupted with a large and sudden burst of X-rays. Credit: ESA/XMM-Newton, A. De Carlo/INAF

ASTRONOMY AND ASTROPHYSICS ㆍ 16 AUGUST 2018

Teens stumble on a new class of astronomical object

Students sifting through archived data find an X-ray flare too brief to belong to an ordinary star.

Secondary-school students have discovered a source of X-rays in the sky that appears to be a new type of astronomical object.

Stars can emit flares of intense X-ray radiation, and a star under the influence of a nearby black hole or neutron star can produce flares that are extremely bright and brief. In search of such objects, a team of students in their final year of secondary school in Sarzana, Italy, analysed data from the XMM-Newton. The results, published in Nature, have created a buzz among astrophysicists.

Selected by a group of High-School students in a stage at INAF/IASF Milano in 2017, September
A puzzling flaring source

- Aligned with Globular Cluster NGC6540
- Type-I burst from a LMXB in NGC6540? *too faint*
- Flare from a G/K star in NGC6540? *too short*
- Flare from a foreground M dwarf? *ruled out by HST photometry*

\[ L_{\text{flare}} \sim 10^{34} \text{ erg/s} \]
\[ L_{\text{pers}} \sim 10^{32} \text{ erg/s} \]

\[ \sigma = 54 \pm 11 \text{ s} \]


HST F555W

CXO

Short term Var.
A distant SN shock breakout

315s duration

$z=0.092 \pm 0.003$

(424 Mpc)

Peak luminosity:

$4.3 \times 10^{43} \text{ erg s}^{-1}$

(0.3-10 keV)

Total energy:

$1.7 \times 10^{46} \text{ erg}$

Similar to SN2008D

(Soderberg+ 2008)

Event rate broadly consistent with the one of ccSNe from optical data

Puzzling pulses from PSR J1311-3430

Selected based on # of BBs and slope changes

An extreme Black Widow system, known to emit MWL flares

Six “pulses” with regular recurrence time

$P = 7450 \pm 40$ s (~124 min)
≠ $P_{orb} \sim 5628$ s (~94 min)

Pulses only seen in X-rays

Initial flare seen both in U and in g’

De Luca+2022, A&A 667, L7
Statistical properties of SFXT flares

Based on BB light curves: 144 flares from 9 sources

Model-independent estimate of temporal properties of flares

Correlation of flares temporal properties vs. other emission properties

Properties of SFXT flares consistent with onset of R-T instability in accreting plasma near the NS magnetosphere.

Sidoli+2019, MNRAS 487, 420
Classification of variability with SOM

Self Organizing Maps – dimensionality reduction and clustering

Based on 31 temporal domain features

Variable sources are clustered -- distinctive regions of the SOM map associated with flares, eclipses, dips, linear light curves, and others.

Kovacevic+2022, A&A 659, A66
Supervised search for flares

Sample of stellar flares generated via visual inspection

Test different selection approaches

- XGBoost trained on full set of temporal features
- XGBoost trained on temporal features excluding model-dependent ones
- Simple cut on statistical improvement of flare model over constant model

Pasquato+2024, in prep
Conclusions

• At the end of 2016, the EXTraS project had produced the most sensitive and thorough search for, and characterization of temporal variability in the soft X-ray sky.

• All results had been released to the community in a public archive. Archive discontinued in mid 2020; products available upon request

• EXTraS results and products are proving to be a very rich resource for investigations in almost all fields of astrophysics

• Updated pipelines for aperiodic variability and pulsations

• Machine learning approach is being tested to screen and classify results

• Deep learning approach is being tested to search for specific phenomena in time series


huge amount of information in serendipitous X-ray data in the time domain

very large space for discoveries

Lessons learnt from XMM will be crucial for a full exploitation of results from future experiments