Characterizing the Aperiodic Variability of 3XMM Sources using Bayesian Blocks

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I will present Bayesian blocks algorithm and its application to XMM sources, statistical properties of the entire 3XMM sample, and a few interesting cases. While XMM-Newton is the best suited instrument for the characterization of X-ray source variability, its most recent catalogue (3XMM) reports light curves only for the brightest ones and excludes from its analysis periods of background flares. One aim of the EXTraS ('Exploring the X-ray Transient and variable Sky') project is the characterization of aperiodic variability of as many 3XMM sources as possible on a time scale shorter than the XMM observation. We adapted the original Bayesian blocks algorithm to account for background contamination, including soft proton flares. In addition, we characterized the short-term aperiodic variability performing a number of statistical tests on all the Bayesian blocks light curves. The EXTraS catalogue and products will be released soon to the community, together with tools that will allow the user to replicate EXTraS results and extend them through the next decade.

3XMM source catalogue and the EXTraS project

- The Third *XMM-Newton* Serendipitous Source Catalogue DR4 (3XMM; Rosen et al. 2016, A&A, 590, A1) was constructed from 7,427 observations (22,512 exposures). It contains 531,261 detections in 0.2-12 keV for the 3 EPIC cameras totaling **1,363,952** objects.
- 3XMM reports time series only for the 23% brightest sources. It characterizes short-term aperiodic variability only with two synthetic parameters (chi-squared vs a constant and excess variance) extracted excluding periods of background flares.
- The EXTraS project (De Luca et al., 2014, arXiv:1503.01497) is the first systematic search for (and characterization of) all variable X-ray sources in the whole 3XMM archive. One of its aims is to characterize the aperiodic variability of the largest possible number of 3XMM sources taking the background contamination into account.

EXTraS Bayesian blocks light curves

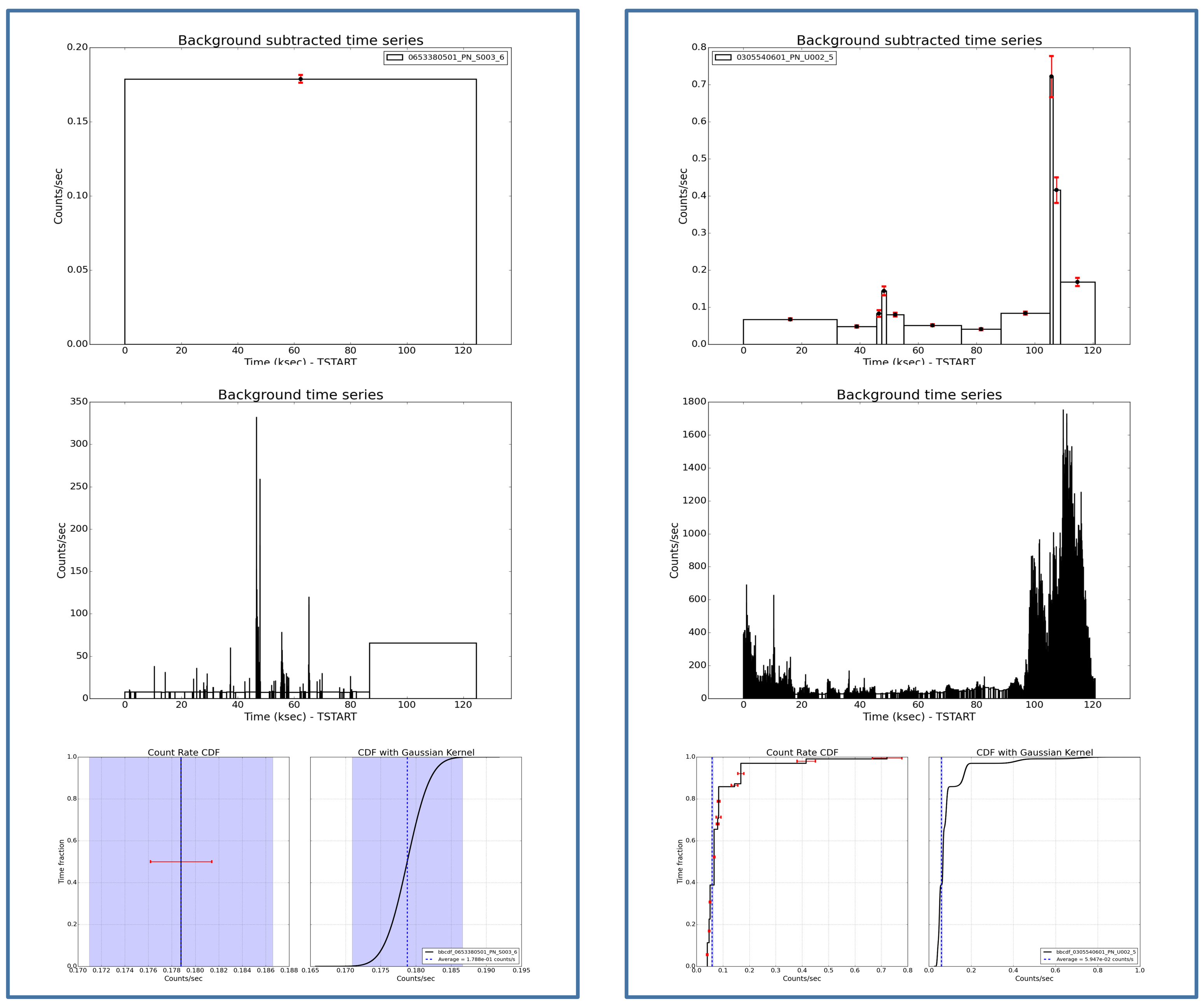

Figure 1: Here are two examples of Bayesian blocks light curves. The **top row** shows the background-subtracted source light curves. The **central row** shows the Bayesian blocks light curve of the background in the same exposure as the light curve above. The **bottom row** shows the cumulative distribution of time spent by the source at a given count rate.
On the left column you see a source light curve with a single block, meaning that the source is not variable (at the 3σ level) even if the background shows a number of flares during the observation. On the right column you see a variable source, and its variability is not correlated with the background one.

Variability parameters

For each Bayesian blocks light curve we extracted several parameters to characterize the aperiodic short-term variability such as:

1. number of blocks (*N*) and fragmentariness (*N-1* per ksec);
2. average count rate, standard deviation, skewness and kurtosis;
3. relative variance (*variance / average rate)* and excess variance;
4. steadiness (*Max((rate**4 / rate_error**2) per ksec*);
5. rate of change of the count rate between consecutive blocks (*slope*);
6. asymmetry of the cumulative distribution of count rates.

We fitted the Bayesian blocks light curves with several models:

1. constant model;
2. polynomial models (linear and quadratic);
3. exponential decay model;
4. constant models with either a flare or an eclipse.

EXTraS is funded by EU within the FP7 Cooperation "Space" call under GA no. 607452. The project started in January 2014, with an expected duration of 36 months. Project coordinator is A. De Luca (INAF/IASF Milano). All references and credits at: http://www.extras-fp7.eu/

Application of Bayesian blocks to 3XMM sources

The Sample

We analyzed a subset of 3XMM sources in each exposure separately.

- We used all the 22,512 exposures from 3XMM.
- We selected all the point-like sources with at least 10 counts expected within the source region (a minimum required for a variability analysis).

As a result, our EXTraS sample contains **1,086,806** 3XMM objects.

The Algorithm

We extracted adaptively binned piecewise constant light curves, namely Bayesian blocks (Scargle et al. 2013, ApJ, 764, 167), dealing carefully with background:

- we considered a discrete application, where the initial set of cells is defined on the basis of the number of events in the source and background regions;
- we used as a fitness function the combined log-likelihood of the source count rate, marginalized over the distribution of the variable background rate. For the background itself we used an innovative technique described in the P06 poster;
- we used a geometric prior on the number of blocks that reflects locally a sigma-cut in the separation of blocks: two blocks are separated only if their count rates are not consistent within *N* sigma, where *N* is given by the prior.

Light curves of different types of X-ray sources

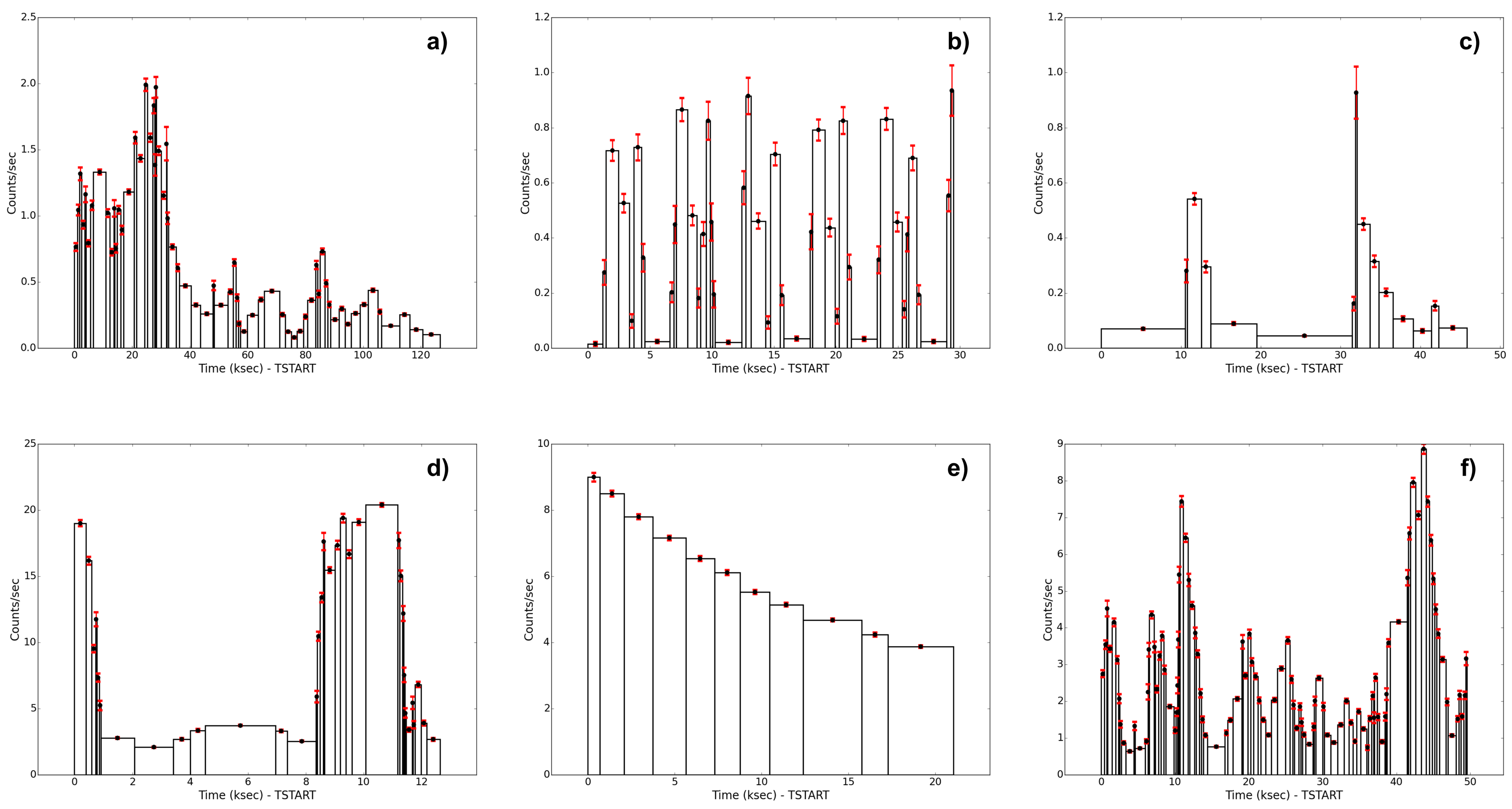

Figure 2: Examples of Bayesian blocks light curves for six types of X-ray sources in the EXTraS source sample. **a)** The active galactic nucleus (AGN) of the NLS1 type IRAS 13224-3809. **b)** A cataclysmic variable (CV) of polar type with eclipse. **c)** Star with several flares. **d)** The super soft X-ray source (SSS) V5116 Sgr. **e)** The gamma-ray burst afterglow (GRB) GRB 090618. **f)** The high mass X-ray binary (HMB) HD 153919.

Variability analysis results

As a result we produced a Bayesian blocks light curve for **801,006** EXTraS objects (97.3% have only 1 block).

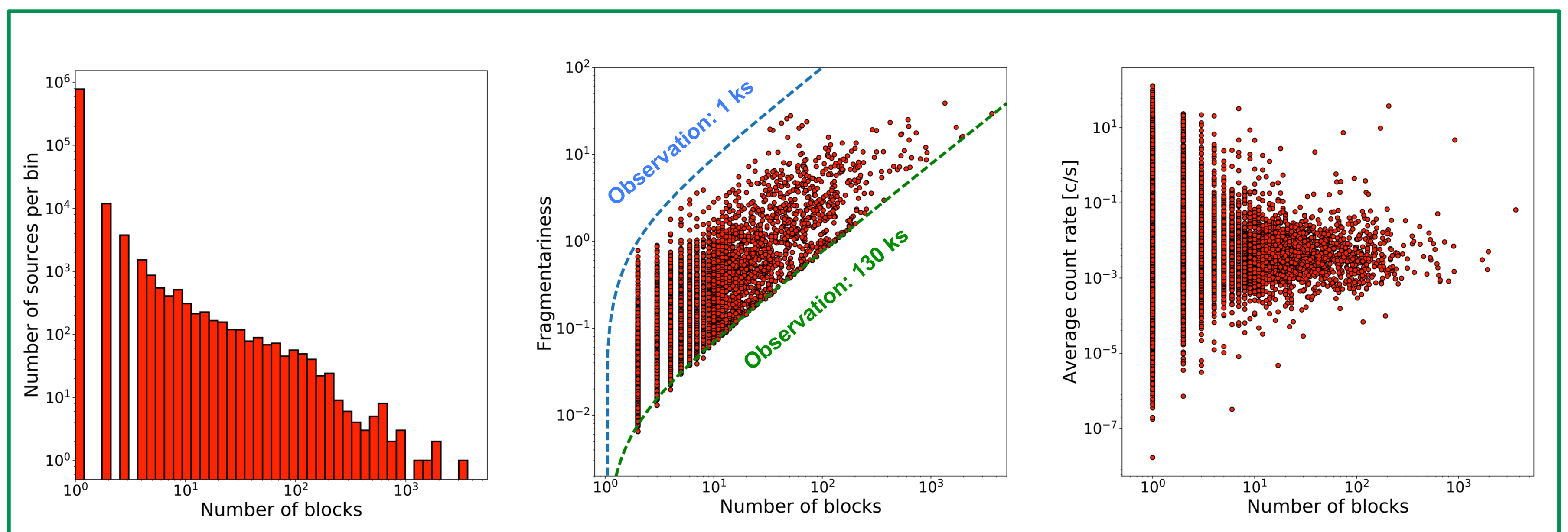

Figure 3: Distribution of some variability parameters within the 801,006 objects of the EXTraS source sample.

Fitting models to Bayesian blocks light curves with more than 1 block we obtained:

- **20,702** (97.2%) objects are not compatible with a constant;
- in **10,612** (49.6%) cases a polynomial model is better than a constant at 3σ c.l.;
- in **1,071** (5%) cases an exponential model is better than a constant at 3σ c.l.;
- in **2,865** (13.4%) and **3,151** (14.7%) cases a model with a flare or an eclipse, respectively, is better than a constant at 3σ c.l..