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Transients in the INTEGRAL/IBIS surveys

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Abstract. While surveys in hard X-ray often concentrate on detection of sources showing persistent or long-term emission, the high variability of the hard X-ray sky requires surveys also to consider transient objects. Here I discuss some of the methods used to enhance sensitivity to transient objects in the INTEGRAL/IBIS surveys, examine their effectiveness, and give some indications on improved methods that may be employed in future surveys.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

The large field of view of coded aperture telescopes like INTEGRAL/IBIS and Swift/BAT make them ideal for producing surveys of the sky. The most recently published surveys of the sky are reaching exposures of 100ks or more over 90% of the sky. The primary motivations for surveys include discovery of new sources, monitoring of existing source populations and the construction of complete samples for further analysis.

The deep sensitivity of modern hard X-ray surveys is largely achieved by stacking large numbers of relatively short exposures taken of the same fields over many years. In the case of IBIS, observations are divided into short pointings, or *science windows* of typically 2000s, separated by short slews during which the instrument pointing direction changes by a few degrees. Each science window can be considered an independent measurement of the flux from all points in the field of view for that pointing.

The final outcome of this stacking analysis approach is essentially used to derive the weighted mean of many 1000s of measurements of source flux taken over a time period in excess of a decade. The weighted mean is used because the measurement quality is non-uniform, being affected by several factors such as exposure time, changing position of the source in the field of view, and the presence of other bright sources in the field. For a *persistent* emitter, the weighted mean of the flux, and the error on that weighted mean, is an excellent estimator of the mean flux and how significantly the mean flux is non-zero; this is the detection significance usually quoted in survey catalogs. In other words, in the assumption that the source is persistent, the significance tells us how confident we can be that we detect a non-zero flux from a given sky position. But how well does this work for variable or transient sources?

One of the biggest problems facing those compiling a transient survey is the lack of a formal definition of 'transient' to work against. The combination of often rapid source variability, and observational factors that mean telescope sensitivity can also change significantly with time means that sources can be detectable at one moment and undetectable later, while never truly ceasing to emit hard X-rays. In the context of hard X-ray surveys, transient can simply be taken to means a source that is not detected during all observations of that sky area.

I will first discuss how transients were detected in the IBIS survey catalogs constructed to date. I will then illustrate the challenges of detecting short-lived transients within the framework of survey analysis with the IBIS science-window based system by means of two case studies. In particular, these case studies will highlight the biases that are introduced because we search for emission on specific timescales, in order to make the problem tractable. Following that, I will show how new methods might be used to derive more information on the emission histories of sources, and be applied more broadly to reduce the biases in present transient searches.

2. Transient detection in the IBIS surveys

The first IBIS survey (Bird, et al. 2004) employed a straightforward stacking analysis, but from the second catalog (Bird, et al. 2006) onward, which analysed ~18 months of data, it was realised that source searches on additional timescales would be needed to optimise the detection of sources that emitted on shorter timescales. Consequently, maps were constructed and searched for the full archive, for each revolution (satellite orbit, ~3 days) and for the periods covering the Galactic Centre Deep Exposure (GCDE) core programme (~1 month each). In the third catalog (Bird, et al. 2007) the GCDE mosaics were replaced by a broader category of *revolution sequences* covering any observing period where the telescope performed a deep exposure on a single field. During the third catalog construction, it was noticed that sources listed in previous catalogs were becoming difficult to detect, and strategies were developed to deal with the increasing baseline of the dataset. The 4th catalog (Bird, et al. 2010) introduced *bursticity* analysis, a sliding-window analysis that sought to detect sources on whatever timescale optimised their detection significance. Most recently, the bursticity method was refined for the catalog of 1000 orbits (Bird, et al. 2016) which had a dataset spanning 8 years of satellite operations, and yet searches were performed for transient emission on timescales down to 0.5 days.

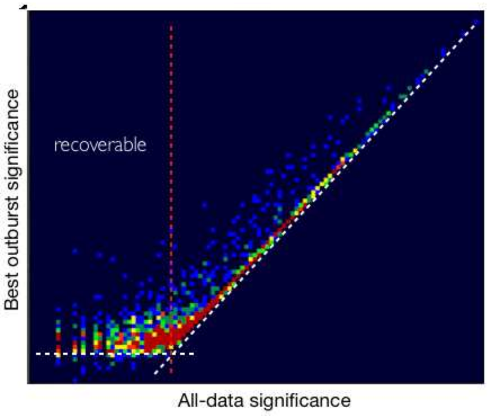

Fig. 1. Source recovery by bursticity.

2.1. Bursticity searches

Figure 1 illustrates how the bursticity method aids the recovery of transient sources in long datasets, plotting the outburst significance against the significance derived from the full light curve. Persistent sources fall along the line of $y = x$ (the diagonal dashed white line), but many sources sit above $y = x$ indicating that their significance can be enhanced in a more limited time period. Sources that fall below the global significance threshold (the vertical red line) but above a burst detection threshold (horizontal dashed white line) can be recovered into the catalogue. The level of the burst detection threshold is determined experimentally - see below.

From the 4th catalog onwards, ~ 10% of the sources are recovered by the use of bursticity.

Bursticity searches are still somewhat biased. To improve the speed of the algorithm, not all window sizes are tested, and the stride (the speed with which the window passes along the light curve) is quite large. This means that not all possible windows are tested, although the assumption is made that the significance is only slowly degraded by using a non-optimal window, and only the very faintest outbursts will be missed in this way.

Of more concern is that bursticity is testing a very large number of non-independent windows, since the stride is typically $\sim 10\%$ of the window length. This makes an analytical determination of the false alarm probability, or the burst detection threshold, difficult. Furthermore, the burst detection threshold depends both on the length and the time structure of the light curve. For the longest light curves for sources in the Galactic Plane, more than 100,000 window tests are performed during a search. In practice, monte-carlo simulations of a flux-randomised light curve with the true temporal structure are used to establish confidence limits. Such tests are really only valid for light curves containing pure white noise, so any long-term source variability affects the determination of the burst detection threshold. With an already CPU-intensive algorithm, this is prohibitive, and the problem of running these tests on every light curve grows quickly as the dataset grows.

3. Case studies

3.1. GRB041219A

GRB041219A was detected early in the INTEGRAL mission timeline at the end of 2004, at the time a rare example of prompt GRB emission seen within the IBIS imaging field of view. GRB041219A was an exceptionally bright and long ($T_{90} \sim 200s$) burst (Gotz, Mereghetti, Shaw, Beck & Borkowski 2004; McBreen, et al. 2006). Due to its nature as a gamma-ray burst, this is an excellent example of a bright, non-recurring transient and demonstrates some of the challenges of dealing with transient sources within a survey context. GRB041219A is detected at a significance of $> 40\sigma$ in the single science window that encompasses its emission.

GRB041219A was included in the third IBIS catalog (the first to include the relevant data) as IGR J00245+6251, on the basis of having been detected in the data for revolution 266 with a significance of 11.5 sigma - no source searches were made at science window level. By the time of the 4th catalog, that detection significance was increased to 27.7 sigma by the bursticity analysis. It is notable that the significance in the stacked image of the entire cat4 dataset is $< 1\sigma$ which would have rendered the source totally undetectable. It can be demonstrated that stacking more than ~5 revolutions of data on the position of GRB041219A is sufficient to drop this very bright transient below the detection threshold in the overall map.

3.2. SAX J1818.6-1703

SAX J1818.6-1703 was also detected early in the INTEGRAL mission timeline, during a bright outburst in Sept 2003 (Grebenev & Sunyaev 2005). Since that time, it has undergone many outbursts during the inferred periastron passages of this 30-day binary. The sum effect of these outbursts has kept SAX J1818.6-1703 constantly visible in stacked images since the first detection, although its significance in stacked maps briefly fell to $\leq 5\sigma$ due to the same issues discussed above.

Bursticity as described so far is intended only as an aid to detection, and returns the time period that maximises source significance. For a source like SAX J1818.6-1703, bursticity may return the brightest outburst, or the full light-curve, depending on the parameters used - and in particular the maximum length of window used can significantly change the outcome of the search. For recurrent transients, a sliding window search with a restricted window length can be used to iteratively search for and exclude parts of the light curve to find multiple outbursts in a light curve. However, such searches are extremely sensitive to the window restrictions, and must effectively be tuned for each source - this is undesirable for automated and unbiased analyses.

4. Future advances

As described, the bursticity method has a number of disadvantages that prevent it being used exhaustively and in an unbiased manner.

4.1. Unbiased searches

The bias in searches come primarily from the arbitrary choice of the minimum and maximum window lengths (both in time and data points), and the stride length. It is therefore logical to seek to eliminate those biases by searching all possible windows, i.e. by establishing the significance of detection between every pair of data points in the light curve. As might be expected, however, this implies a very large number of tests.

One advantage of the method is that it allows a more informative display of the search results as a 2D grid of significances with the start and end science window indices forming the axes of the map. Taking the first of the test cases described above, Figure 2 shows the 2D significance map for the light curve of GRB041219A. A single bright area is obvious, showing the one outburst. The bright spot on the $y = x$ line shows that the optimal significance is close to where the start and end light curve indices are very similar, and so the outburst is short. The fading area moving towards earlier start times and/or later end times shows how the significance declines as less optimal windows are used. A slice across the map can be used to show that windows longer than 5 revolutions result in significances below the detection cut.

Reference to the equivalent figure for SAX J1818.6-1703 (Figure 3) demonstrates the extra information provided by one pass of the exhaustive search. Multiple bright spots are seen along the line of $y = x$, identifying individual short outbursts in the light curve. The cumulative effect of all the outbursts to the whole light-curve significance (at the top-right of the map) can also be seen.

A GPU-based exhaustive search algorithm, written in the CUDA language has been developed, and demonstrated to be $\sim 250\times$ faster than the equivalent CPU-based code. This not only makes the intensive search practicable, but it also allows for comprehensive monte-carlo tests to be used on individual light curves to properly establish confidence limits.

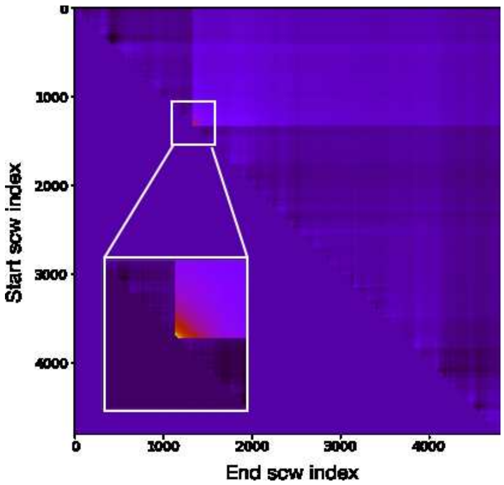

Fig. 2. Exhaustive grid search for GRB041219A light curve.

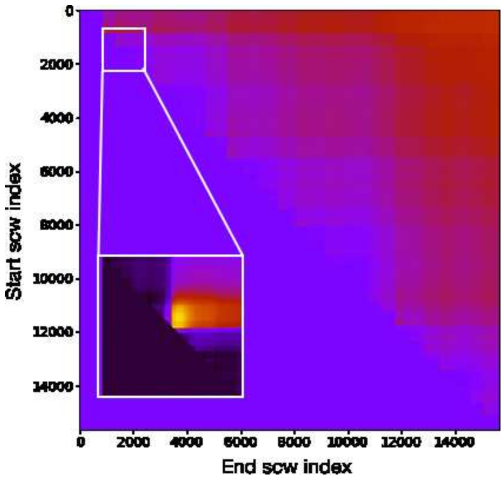

Fig. 3. Exhaustive grid search for SAX J1818.6-1703 light curve.

5. Conclusions

Current methods allow us to search for short-term and transient emission from known sources in the X-ray sky with good confidence, but are inherently biased in the forms of emission they can discover. Carrying out blind searches of archival data to discover similar sources is technically very challenging. New techniques for analysing survey data from hard X-ray telescopes will eventually allow more unbiased samples of sources to be constructed, independent of their emission timescales. However, the technical challenges associated with these methods in practice are formidable.

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References

Bird, A. J., et al. 2004, ApJ, 607, L33
Bird, A. J., et al. 2006, ApJ, 636, 765
Bird, A. J., et al. 2007, ApJS, 170, 175
Bird, A. J., et al. 2010, ApJS, 186, 1
Bird, A. J., et al. 2016, ApJS, 223, 15
Gotz, D., et al. 2004, GRB Coordinates Network, 2866, 1
Grebenev, S. A., Sunyaev, R. A. 2005, Astronomy Letters, 31, 672
McBreen, S., et al. 2006, A&A, 455, 433