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The XRT catalogues

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In the ten years of operation, the X-ray telescope on board *Swift* has collected a wealth of X-ray data. This has resulted in the production of many catalogues. In this proceeding, based on a review talk given at the 'Swift: 10 Years of Discovery' conference which celebrated Swift's tenth complete year in orbit, I give a brief overview on six of the catalogues produced by the *Swift*-XRT team: three Gamma Ray Burst catalogues, and three serendipitous source catalogues.

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1. Introduction

The *Swift* satellite (1) was launched on 2004 November 20, and recently celebrated ten highly productive years of operation, that have seen it repeatedly ranked as the top-performing mission in NASA's Senior Review. In addition to the Burst Alert Telescope (BAT) (2) and UV/Optical Telescope (UVOT) (3), it contains an X-ray Telescope (XRT) (4), with an energy range of 0.3–10 keV and a peak effective area of 110 cm^2 at 1.5 keV.

Swift observations have powered a wide range of ground-breaking science, from its primary mission goal of studying Gamma Ray Bursts (GRBs) through to the hundreds of target of opportunity observations performed every year. The objects studied range from Novae (e.g. (5; 6)), to Supergiant Fast X-ray Transients (e.g. (7)), to exotica such as potential gravitational wave (8) or neutrino (9) sources. These proceedings give overviews and examples of many such objects.

As well as the many works that have been published studying individual objects and samples of a given class of X-ray emitter, several catalogues have also been produced. In this work I give a brief overview of the GRB catalogues, and the serendipitous source catalogues produced by the XRT team. This is not intended to be a complete detailed description of those works, nor does it claim to be complete or unbiased. It is instead an overview of the catalogues, and the interested reader is strongly encouraged to read the catalogue papers themselves, which are cited throughout this work.

2. GRB catalogues

There are several papers from early in the life of *Swift* which could be classed as GRB catalogue papers. For example, (10) provided X-ray positions for 68 GRBs based on a revised calibration, and (11) used an improved astrometric technique to improve the XRT positions of 179 GRB afterglows. (12) took a sample of X-ray afterglows and fitted them with a common model. However, here I will focus only on the three XRT-team led papers which analysed large samples of GRBs and reported on the properties of their objects as a whole. These catalogues, in order of publication, are those of Evans et al. (13), Racusin et al., (14) and Margutti et al. (15).

2.1 Evans et al.

The Evans et al. (2009) catalogue (13) presented an homogeneous analysis of 318 GRBs detected with the XRT up to 2008 July 23. As well as improved positions, they gave power-law fits to light curve and spectrum of each afterglow and, for afterglows with broken power-law fits, spectra for each segment. This allowed them to analyse the statistical properties of the different phases of the afterglow decay, and analyse the different light curve morphologies. Based on this analysis they argued that the different light curve morphologies seen are consistent with a single mechanism. However, comparing of the properties of these bursts with the predictions of the forward shock model, they found that, for a large fraction of GRBs, energy injection into the forwards shock would need to continue for many days after the burst to reconcile the observations with theory.

Since publication of the paper, a 'live' version of the catalogue has been posted online at http://www.swift.ac.uk/xrt_live_cat. This is populated by automated analysis of new GRBs, and

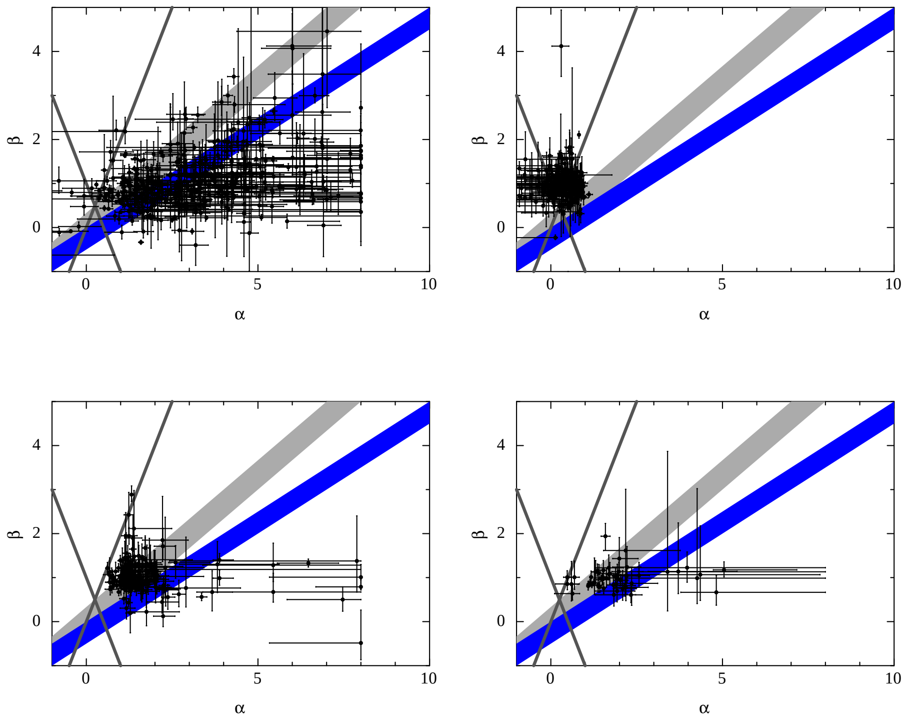

Figure 1: The spectral energy index, β, plotted against the temporal decay index, α, for the GRBs classified as having canonical afterglow light curves by the online live XRT GRB catalogue. This plot was taken from the online catalogue on 2015 Feb 27. The 4 panels show: *top left*: the steep decay phase; *top right*: the plateau phase, *bottom left*: the normal, post-plateau decay, and *bottom right*: the phase after an extra break after the plateau end, which is seen in some bursts (and usually interpreted as a jet break). The grey thick bands show the region permitted by the standard external shock model in the slow cooling regime, grey and blue referreing to pre/post jet break. The narrow grey lines indicate the fast cooling regime. Taken from (13).

contains versions of the main tables and figures from the paper. For example, Fig. 1 shows the latest 'closure relationship' plots for bursts classified having a 'canonical' afterglow light curve. For each of the four phases of the light curve, the spectral energy index (β, where $E \propto E^{-\beta}$, is plotted against the temporal decay index (α, where $L \propto t^{-\alpha}$) for all of the canonical bursts, with the regions permitted by standard forward shock theory also indicated.

2.2 Racusin et al.

Racusin et al., (2009) (14) performed a similar analysis to Evans et al. (13), calculating light curve fits to all GRBs detected by XRT up to 2007 December, and performing spectral analysis of the different light curve decay segments. Their focus however was on jet breaks, considering why very few jet breaks had been seen in XRT afterglow data. They considered a large range of theoretical models, including those from structured jets, or jets with lateral spreading. For every break in a light curve after which the decay steepened, they considered the possible cause of the break, determining which theoretical models were consistent with the temporal and spectral properties of the afterglow on both sides of the break.

Based on this analysis they identified strong evidence for jet breaks in 12% of the GRBs in their sample. A further 30% of GRBs showed evidence for jet breaks, although this could not be absolutely confirmed. They found a wide range in the jet break times, with a median time of $\sim$1 day.

2.3 Margutti et al.

Margutti et al. (2013) (15) presented a sample of 650 GRBs, for which, as with the previous works, they performed spectro-temporal analysis. However, they also considered the subset of those GRBs which had a measured redshift. For this subsample, which comprised 79 long GRBs and 9 short GRBs, they constructed rest-frame light curves showing the evolution of the unabsorbed luminosity. This allowed these authors, in contrast to the previous works, to consider the intrinsic properties of the GRBs, rather than the observed properties. They also considered the rest-frame properties of the prompt emission, such as the peak energy in the spectrum, and the isotropic-equivalent energy release in the prompt phase.

They then performed a search for correlations between the various properties they had derived, confirming, for example, the relationship between the energy contained in the prompt and afterglow phases (previously reported by (12)). They also showed, for example, that the luminosity at the end of the plateau phase is correlated with the duration of that phase. These relationships held for the long GRBs, but they found that short GRBs were discrepant. They were however, able to produce a three-parameter correlation linking the isotropic-equivalent luminosity the X-ray afterglow, with that of the prompt phase and the peak energy of the prompt spectrum. This correlation holds for both short and long GRBs.

3. Serendipitous source catalogues

The Swift-XRT has a field of view of radius $\sim 12.3'$ with a point-spread function half-energy-width of $18''$ (16). Consequently, the majority of the detector is not imaging the source which is the target of whatever *Swift* is observing, and is thus available for serendipitous science. Here I will summarise the three serendipitous point-source catalogues produced by the XRT team, in publication order. These are the SwiftFT catalogue (17), the 1SWXRT catalogue (18) and the 1SXPS catalogue (19). There is also a catalogue of extended sources available, SXCS (20), however this was not led by the XRT team and will not be discussed in these proceedings.

3.1 SwiftFT

The first of the serendipitous was published by Puccetti et al. (2011) (17), and was named in memory of Francesca Tamburelli, who contributed to the development of the XRT data reduction software. This catalogue was designed to exploit the *Swift* observations of GRBs, which consist of many repeated observations of the same patch of sky. For each GRB, the observations were merged together to give a single image, resulting in a catalogue covering 33 square degrees with exposures ranging from 10ks to over 1 Ms. An additional benefit of this approach is that the target of the observation – the GRB – is well known and well-localised, thus it can be excluded and and only truly serendipitous sources are included in the catalogue.

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The focus of this catalogue is on Active Galactic Nucleii (AGN), and they report a total of 9387 point-like sources, with 7071 of them lying at high Galactic latitudes ($|b| > 20^\circ$). The typical sensitivity of the catalogue is 5×10^{-15} erg cm^{-2} s^{-1}, and it covers 33 square degrees.

The SwiftFT catalogue can be explored online at: http://www.asdc.asi.it/xrtgrbdeep_cat/

3.2 1SWXRT

The 1SWXRT catalogue (18) built on the techniques employed for the SwiftFT work, but instead of merging repeated observations of the same patch of sky, each observation was analysed individually. This catalogue was also not limited to the GRB fields, but included every field with an exposure of more than 500 s in Photon Counting (PC) mode: the mode in which XRT retains 2-D imaging information.

This work contains $\sim$ 89,000 X-ray detections, a number which was reduced to 85,000 when those affected by pile-up (where the source is too bright for the CCD to correctly distinguish indivual photons from each other) were discarded. These detections correspond to $\sim$36,000 distinct X-ray sources. For each source, the catalogue contains the count-rate and fluxes in three energy bands, with a typical sensitivity in the 0.3–10 keV 'full' band of $\sim 10^{-11}$ erg cm^{-2} s^{-1}. The catalogue covers 1,300 square degrees.

The 1SWXRT catalogue can be explored online at: http://www.asdc.asi.it/1swxrt/

3.3 1SXPS

The most recent serendipitous source catalogue is the 1SXPS catalogue (19). This combined the approaches of the SwiftFT and 1SWXRT works, in that source detection was performed on every individual observation (this time with a minimum exposure of 100 s), and also on deep images created by combining multiple observation of the same sky location. The latter were created for all locations on the sky observed more than once, not just the GRB fields. Additionally, a new source detection algorithm was created for the 1SXPS catalogue, designed to detect fainter objects. This catalogue contains $\sim$150,000 X-ray source, of which just over 82,000 were previously uncatalogued in X-rays. The typical sensitivity of this catalogue in a single observation was 3×10^{-13} erg cm^{-2} s^{-1}, and it covers 1,905 square degrees ($\sim$ 5% of the sky), making it the most sensitive and widest XRT serendipitous source catalogue to date. The location of the XRT fields included in 1SXPS are shown in Fig. 2.

The 1SXPS catalogue focussed particularly on the creation of source variability, providing light curves in 4 energy bands, and two hardness ratio time series, for each detected source. Variability tests were then performed, revealing nearly 30,000 sources which were inconsistent with being constant, at the 3-σ level. For the brightest sources, the 1SXPS catalogue contains spectra, automatically fitted with a power-law and APEC model. All light curves, spectra, images and FITS files are available for download via the catalogue web pages at http://www.swift.ac.uk/1SXPS.

4. Conclusions

In ten years of operation, *Swift* has produced a wealth of X-ray data, sufficient to populate six distinct catalogues. Three of these focus on GRBs, and cover general population properties, specific studies of possible jet breaks, and the rest frame properites and parameter correlations. The

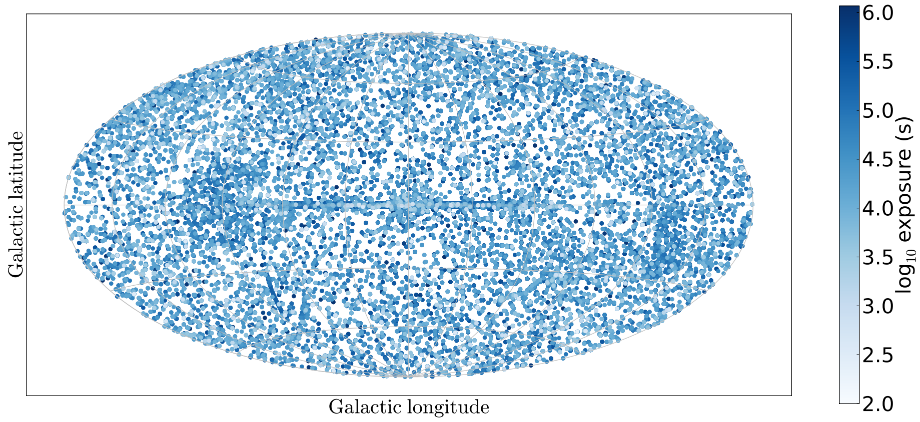

Figure 2: The locations of the XRT fields included in the 1SXPS catalogue, in Galactic coordinates. The colours of the points indicate the exposure time at that location. The points are larger than the field of view. Taken from (19).

other three catalogues focus on exploiting the wealth of serendipitous science that XRT's moderate field of view and narrow point-spread-function yield. One of these focusses on the deepest observations with XRT, one considers all individual observations, and the third combines both approaches, and focusses on increased sensitivity and the creation of source products. Between these three catalogues over 150,000 X-ray sources have been detected.

5. Acknowledgements

This work is an attempt to summarise the six main catalogues produced by the XRT team, and I would like to thank all those who contributed to the production of those catalogues – and apologise for any bias in this review towards the two papers which I led.

I first joined the *Swift*-XRT team in 2006, on a 6-month contract, and nine years on I am still enjoying the job. I acknowledge the UK Space Agency for supplying the funding that has kept me in post over this time. It has been a great pleasure to work with colleagues from all three instruments and from around the globe as well as at the University of Leicester, and a real privalege to be involved in such a successful science mission. Here's to another ten years!

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