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High-Energy Transients: Thermonuclear (Type-I) X-Ray Bursts

INVITED TALK

D. K. Galloway[1,2], **Z. Johnston**[1,2], **A. Goodwin**[1,2] **and A. Heger**[1,2,3]

[1]School of Physics & Astronomy, Monash University, Melbourne, Australia
[2]Monash Centre for Astrophysics (MoCA), Monash University, Melbourne, Australia
[3]Tsung-Dao Lee Institute, Shanghai, China
email: `duncan.galloway@monash.edu`

Abstract. Many distinct classes of high-energy variability have been observed in astrophysical sources, and over a range of time-scales. The widest range, spanning microseconds to decades, is found in accreting, compact, stellar-mass objects, including neutron stars and black holes. Neutron stars are of particular observational interest as they exhibit surface effects giving rise to phenomena – such as thermonuclear bursts and pulsations – not seen in black holes.

This talk reviewed briefly the present understanding of thermonuclear (Type-I) X-ray bursts – events that are powered by an extensive chain of nuclear reactions which in many cases are unique to the environments. Thermonuclear bursts have been exploited over the last few years as an avenue to measure a neutron star's mass and radius, although the contribution of systematic errors to the measurements remains contentious. We described recent efforts to match burst models to observations better, with a view to resolving some of the astrophysical uncertainties relating to those events. Our efforts have good prospects for providing information that is complementary to nuclear experiments.

Keywords. Stars: neutron, X-rays: bursts, nuclear reactions

1. Introduction

The high-energy sky is fundamentally dynamic. From the early 1970s, when X-ray (and higher-energy) bands became opened to observers, variability on time-scales of decades down to milliseconds has been discovered. X-ray binaries, which show accretion-rate variations, transient outbursts, pulsations and quasi-periodic oscillations, span that entire range.

Low-mass binaries hosting neutron stars are thought to accrete over gigayear time-scales (e.g., Podsiadlowski *et al.* 2002), sufficient to reduce the magnetic field to a point where it is dynamically unimportant. These systems, i.e., thermonuclear (Type-I) X-ray bursts, exhibit a unique type of variability over time-scales of seconds to minutes. Thermonuclear bursts occur when accreted fuel undergoes unstable ignition, producing bright X-ray flashes ($\sim 10^{38}\,\mathrm{erg\,s^{-1}}$); a review has been given by Galloway & Keek (2017). Bursts typically ignite via the triple-alpha reaction, and if hydrogen is present they also burn via the (αp) and *rp* processes. Much work (e.g., Schatz *et al.* 2001) has focussed on the *rp*-process, which can produce heavy proton-rich nuclei in the burst ashes. But many of the individual reactions have rates that are poorly measured experimentally, and involve nuclei whose masses are uncertain.

While accretion rate and fuel composition are the primary determinants of the burst properties, the burst profiles also encode information about the neutron star's mass and radius via the gravitational redshift, as well as the individual nuclear reactions that power them (e.g., Cyburt *et al.* 2016, Schatz & Ong 2017).

Much effort over the past decade has been applied to measuring mass and radius from burst spectra (e.g., Özel *et al.* 2016), but there remain fundamental uncertainties (and disagreements) about which bursts to choose, and what assumptions to make about the spectral shape (e.g., Steiner *et al.* 2013, Poutanen *et al.* 2014). Such issues are symptomatic of some remaining deep uncertainties about the burst physics, and motivate further research (both observational and numerical) to resolve and improve our ability to constrain the properties of the burst hosts. The talk described prospects for resolving these uncertainties via detailed comparisons between observations and numerical models.

2. Observations

Our knowledge of the phenomenology of thermonuclear bursts has grown through extensive observations made by a series of X-ray missions. Notable examples include *BeppoSAX*, a mission featuring the Wide-Field Camera (WFC) operating through the 1990s (e.g., Boella *et al.* 1997, Jager *et al.* 1997, in't Zand *et al.* 2004), the *Rossi X-ray Timing Explorer* (*RXTE*) with the Proportional Counter Array (PCA), providing high sensitivity and fast timing capability and operational between 1995 December and 2012 January (Jahoda *et al.* 1996), and the hard X-ray and γ-ray observatory *INTEGRAL*, with the wide-field Joint European X-ray Monitor (JEM-X), operational from 2002 onwards (Winkler *et al.* 2003, Lund *et al.* 2003).

Other currently-active missions with capabilities suited to observations of bursts include (a) *Swift* (Gehrels *et al.* 2004) and (b) *MAXI* (Matsuoka *et al.* 2009), each with wide-field instruments ideal for detecting new transients and rare events like superbursts, (c) *NUSTAR* (Harrison *et al.* 2010), with sensitivity to hard X-rays (up to 80 keV), (d) *ASTROSAT* (Singh *et al.* 2014), launched in September 2015, featuring the Large-Area X-ray Proportional Counter (LAXPC) with comparable capabilities to the *RXTE* PCA, and (e) *NICER* (Gendreau *et al.* 2016), deployed to the International Space Station in 2017 June, with an observational programme focussing on X-ray pulsations and bursts.

The data accumulated to date have revealed a remarkable diversity of burst behaviour. Among the usual frequent, quasi-regular bursts (lasting up to a minute and separated by a few hours), the most intense events usually exhibit photospheric radius expansion. Such events are thought to reach the (local) Eddington flux limit, so additional energy input goes into expansion of the photosphere. These bursts serve as an approximate standard candle, enabling the distance to the bursting source to be estimated (see, e.g., Kuulkers *et al.* 2003). Intermediate-duration bursts, lasting minutes (and with correspondingly longer recurrence times than typical bursts) are observed in low accretion-rate systems and are attributed to the burning of large reservoirs of pure He (e.g., Falanga *et al.* 2009). Even longer events, lasting hours, are classified as superbursts and are probably powered by carbon produced as a by-product of the burning during more frequent bursts (see Cornelisse *et al.* 2000, in't Zand 2017). It has been suggested that multi-peaked bursts arise as a result of 'nuclear waiting points': specific reactions through which the burning products flow particularly slowly (e.g., Fisker *et al.* 2004).

3. Analysis of Large Burst Samples

Given the diversity of burst phenomenology, the assembly and analysis of large samples of bursts is important for identifying suitable candidates for analysis (e.g., Cornelisse *et al.* 2003, Galloway *et al.* 2008). A more recent project, the Multi-INstrument Burst ARchive

(MINBAR (http://burst.sci.monash.edu/minbar), is seeking to combine data from *multiple* instruments, and is currently under assembly. The MINBAR sample includes bursts observed by *BeppoSAX*/WFC, *RXTE*/PCA, and *INTEGRAL*/JEM-X, up to the end of the *RXTE* mission in 2012 January. It will be comprised of more than 7000 events from 85 (of 110 known) sources. Analysis of the sample is expected to provide an improved 'global' view of burst behaviour and increased numbers of rare events.

Analysis of preliminary sample data has already led to some significant results. Spectral analysis of the bursts observed with the highest-sensitivity instruments suggests that the persistent emission increases temporarily during bursts (Worpel *et al.* 2013, 2015). That result has been corroborated by a fortuitously simultaneous observation of a burst with the *Chandra X-ray Observatory* (in't Zand *et al.* 2013), demonstrating that the increase factor can be as high as 20. Such an increase may be expected as a result of a temporary increase in accretion through the disk, resulting from Poynting-Robertson drag on the disk material by the burst. The result further suggests that the traditional approach for time-resolved spectroscopy, requiring subtraction of the pre-burst emission and fitting with a blackbody (e.g., Kuulkers *et al.* 2002), may be inadequate for very high-quality data.

Short recurrence-time bursts have been shown to be associated only with systems that accrete hydrogen-rich material, supporting the view that these events arise from fuel that is left unburnt from a previous event (Keek *et al.* 2010). A survey of the properties of burst oscillations, and transient quasi-periodic intensity variations detectable around the peak of bursts from some sources, has been presented by Ootes *et al.* (2017).

4. Burst Models

It is generally not possible to infer directly the system parameters (neutron-star mass, radius, fuel composition, etc.) from the bursts or the persistent emission observations. We must therefore make comparisons with burst models. The current state of the art is represented by 1-D codes that have adaptive nuclear reaction grids, like Kepler (Woosley *et al.* 2004) and Mesa (Paxton *et al.* 2015).

Much of the modelling effort to date has focussed on matching the behaviour of GS 1826−24, the 'Clocked Burster', which is unique among burst sources for its consistent, regular bursts with uniform light-curves. This behaviour has been observed over a range of accretion rates sampled at different epochs (e.g., Ubertini *et al.* 1999). Early comparisons of burst properties measured by *RXTE* with simple ignition models suggested low-metallicity fuel (Galloway *et al.* 2004). In contrast, subsequent analyses, also incorporating a comparison between an observed light-curve and a model derived with the Kepler hydrodynamics code, indicated solar composition (Heger *et al.* 2007). More recent, ongoing work with more comprehensive comparisons has suggested that the degree of agreement may have been overestimated owing to the restriction of comparisons at a single epoch.

Efforts to improve the fidelity of these codes are ongoing, for example via a working group to compare the results of different models, assembled as part of the activities of the Joint Institute of Nuclear Astrophysics Centre for the Evolution of the Elements (JINA-CEE, http://jinaweb.org). There is also a need to improve the access that observers have to results from modelling. For example, a large sample of model results obtained with the Kepler code has been analysed by Lampe *et al.* (2016); various parameters (burst recurrence time, light-curves etc.) are available at http://burst.sci.monash.edu/kepler.

In order to anticipate the likely impact that comparisons between models and observation can have on the rates of the nuclear reactions which drive the burst, sensitivity studies (Cyburt *et al.* 2016) have been carried out to identify those reactions which have the most influence on the burst light-curve.

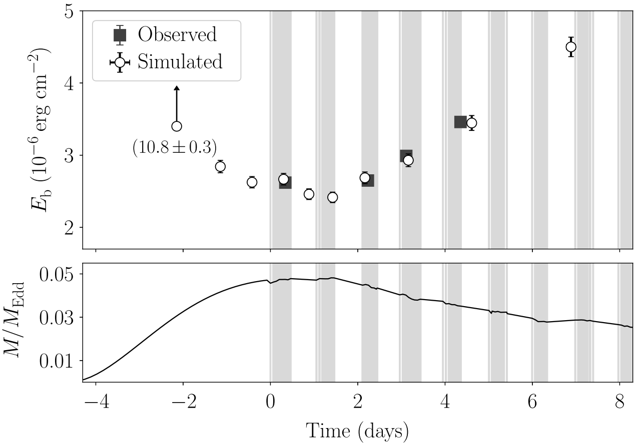

Figure 1. Results from time-dependent KEPLER model simulations of burst activity during the 2002 outburst of SAX J1808.4−3658. *Upper:* the fluence, E_b, of a modelled burst sequence (*open symbols*) compared to the four observed bursts (*filled symbols*). Note the good agreement between the predicted fluence and time of the bursts; the vertical grey bands indicate the instrument's windows for observation. *Lower:* the inferred evolution of the accretion rate during the outburst, plotted as a fraction of the Eddington rate. (From Johnston *et al.* 2018, slightly modified).

5. Recent Work and Astrophysical Uncertainties

Some of the recent results demonstrate the potential of the comparisons between model and observation, but also highlight remaining issues that must be considered. The ultimate goal is to match models to observations, taking into account the astrophysical uncertainties, and hence to probe the nuclear physics of the bursts.

Obtaining suitable data for comparing models with observation can be a challenge. Data from low Earth-orbit satellites, with their ∼90-min orbits, are typically interrupted within each orbit, with maximum duty cycles of ∼60%. Gaps of that nature introduce ambiguities, usually of a few hours, into measurements of recurrence times. On the other hand, other systems exhibit much less regular bursts, and also may not conveniently vary in accretion rate to provide burst samples with different ignition conditions. To address this challenge, we have assembled from MINBAR a set of observed bursts with well-constrained recurrence times (see Galloway *et al.* 2017, and http://burst.sci.monash.edu). It is anticipated that this sub-sample will serve as test cases for numerical codes attempting to understand variations between models. Where feasible, the sample includes observations at different accretion rates specifically to enable multi-epoch comparisons resolve astrophysical uncertainties.

An alternative route is to employ short-duration transients, which may exhibit increases in their accretion rate of orders of magnitude during a day, and then decline. The accretion-powered millisecond pulsar SAX J1808.4–3658 exhibits such outbursts every few years, and has previously been a subject for comparing observations of bursts with simple ignition models (Galloway & Cumming 2006). More recently, the inferred mass accretion history during such outbursts has been used as input to simulate the bursts modelled with the KEPLER code over an entire week-long outburst (Johnston *et al.* 2018); see also Fig. 1. Such simulations demonstrate systematic differences in predicted recurrence times when the accretion rate is rising or falling, compared to the predicted recurrence time obtained by adopting the average accretion rate over the burst interval. That result may have implications for understanding the response of the burning layer to a varying accretion rate.

Comparisons between models and observation face significant challenges. Astrophysical uncertainties introduce biases and degeneracy in the comparisons. For example, the distances to the bursting sources are mostly only poorly known, introducing uncertainties about the burst energetics (e.g., Galloway *et al.* 2008). The measured burst flux is expected to be enhanced or attenuated owing to the anisotropy of the environment, specifically the accretion disk (He & Keek 2016). Estimates of accretion rates are made via the persistent emission, which suffers from the same problem but with a different geometry factor. In addition, the burst and persistent intensity are typically measured across a limited instrumental passband, introducing additional errors when estimating the bolometric luminosities (see Thompson *et al.* 2008). The burst emission is also affected by gravitational redshift, which is poorly constrained because of uncertainties in source mass and radius.

6. Summary and Future Prospects

Some fundamental shortcomings remain in our understanding of the various burst phenomena. However, we now have access to a substantial accumulated set of observed data to analyse, and multiple model codes with which to simulate bursts and thence infer system parameters. Software development is under way to provide code that can model these various effects and possibly squeeze out the corresponding systematic uncertainties so as to constrain the properties of interest. From that perspective the prospects for future comparisons between models and observations are excellent; furthermore, incorporating known sensitivities in the nuclear physics may enable us to constrain specific masses and/or reaction rates, providing complementary information to nuclear experiments. We also enjoy a continuing prospect of exciting new data to be obtained with upcoming missions such as *ASTROSAT* and *NICER*.

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References

Boella, G., Butler, R. C., Perola, G. C., *et al.* 1997, *A&AS*, 122
Cornelisse, R., Heise, J., Kuulkers, E., Verbunt, F., & in 't Zand, J. J. M. 2000, *A&A*, 357, L21
Cornelisse, R., *et al.* 2003, *A&A*, 405, 1033
Cyburt, R. H., Amthor, A. M., Heger, A., *et al.* 2016, *ApJ*, 830, 55
Falanga, M., Cumming, A., Bozzo, E., & Chenevez, J. 2009, *A&A*, 496, 333
Fisker, J. L., Thielemann, F.-K., & Wiescher, M. 2004, *ApJ*, 608, L61
Galloway, D. K. & Cumming, A. 2006, *ApJ*, 652, 559
Galloway, D. K., Cumming, A., Kuulkers, E., *et al.* 2004, *ApJ*, 601, 466
Galloway, D. K., Goodwin, A. J., & Keek, L. 2017, *PASA*, 34, e019
Galloway, D. K. & Keek, L. 2017, arXiv:1712.06227

Galloway, D. K., Muno, M. P., Hartman, J. M., Psaltis, D., & Chakrabarty, D. 2008, *ApJS*, 179, 360

Gehrels, N., *et al.*, 2004, *ApJ*, 611, 1005

Gendreau, K. C., *et al.* 2016, *Proc. SPIE*, 9905

Harrison, F. A., *et al.* 2010, *Proc. SPIE*, 7732

He, C.-C. & Keek, L. 2016, *ApJ*, 819, 47

Heger, A., Cumming, A., Galloway, D. K., & Woosley, S. E. 2007, *ApJ*, 671, L141

in't Zand, J., *et al.* in: E.P.J. van den Heuvel, R. A. M. J. Wijers, & J. J. M. in't Zand (eds.), *The Restless High-Energy Universe*, Proc. 2^{nd} BeppoSAX Conf., Vol. 132, p. 486

in't Zand, J. 2017, in: M. Serino, M. Shidatsu, W. Iwakiri, & T. Mihara (eds)., *7 years of MAXI: Monitoring X-ray Transients*, https://indico2.riken.jp/indico/conferenceDisplay.py?confId=2357, p. 121

in't Zand, J. J. M., *et al.* 2013, *A&A*, 553, A83

Jager, R., *et al.* 1997, *A&AS*, 125, 557

Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayer, T., Zhang, W., & Morgan, E. H. 1996, *Proc. SPIE*, 2808, 59

Johnston, Z., Heger, A., & Galloway, D. K. 2018, *MNRAS*, 477, 2112

Keek, L., Galloway, D. K., in't Zand, J. J. M., & Heger, A. 2010, *ApJ*, 718, 292

Kuulkers, E., den Hartog, P. R., in't Zand, J. J. M., Verbunt, F. W. M., Harris, W. E., & Cocchi, M. 2003, *A&A*, 399, 663

Kuulkers, E., Homan, J., van der Klis, M., Lewin, W. H. G., & Méndez, M. 2002, *A&A*, 382, 947

Lampe, N., Heger, A., & Galloway, D. K. 2016, *ApJ*, 819, 46

Lund, N., *et al.* 2003, *A&A*, 411, L231

Matsuoka, M., *et al.* 2009, *PASJ*, 61, 999

Ootes, L. S., Watts, A. L., Galloway, D. K., & Wijnands, R. 2017, *ApJ*, 834, 21

Özel, F., Psaltis, D., Güver, T., Baym, G., Heinke, C., & Guillot, S. 2016, *ApJ*, 820, 28

Paxton, B., *et al.* 2015, *ApJS*, 220, 15

Podsiadlowski, P., Rappaport, S., & Pfahl, E. D. 2002, *ApJ*, 565, 1107

Poutanen, L., *et al.* 2014, *MNRAS*, 442, 3777

Schatz, H., *et al.* 2001, *Phys. Rev. Let.*, 86, 3471

Schatz, H. & Ong, W.-J. 2017, *ApJ*, 844, 139

Singh, K. P., *et al.* 2014, *Proc. SPIE*, 9144

Steiner, A. W., Lattimer, J. M., & Brown, E. F. 2013, *ApJ*, 765, L5

Thompson, T. W. J., Galloway, D. K., Rothschild, R. E., & Homer, L. 2008, *ApJ*, 681, 506

Ubertini, P., Bazzano, A., Cocchi, M., Natalucci, L., Heise, J., Muller, J. M., & in 't Zand, J. J. M. 1999, *ApJ*, 514, L27

Winkler, C., *et al.* 2003, *A&A*, 411, L1

Woosley, S. E., *et al.* 2004, *ApJS*, 151, 75

Worpel, H., Galloway, D. K., & Price, D. J. 2013, *ApJ*, 772, 94

Worpel H., Galloway, D. K., & Price, D. J. 2015, *ApJ*, 801, 60