SF2A 2008
C. Charbonnel, F. Combes and R. Samadi (eds)

X-RAY BURSTS FROM THE GALACTIC CENTER: THE CASE OF SLX 1737–282 AND GRS 1741.9–2853

Trap, G.[1,2], Falanga, M.[2], Goldwurm, A.[1,2] and Terrier, R.[1]

Abstract. The center of our galaxy harbors a whole population of neutron stars in low mass X-ray binaries. Most of these systems are characterized by regular fast rises followed by exponential decays of their X-ray luminosities, on timescales ranging from seconds to hours. These "X-ray bursts" are now firmly believed to result from unstable thermonuclear burning of accreted material onto the surface of the neutron stars. In early 2007, while surveying the Galactic Center, the *INTEGRAL* satellite recorded a new long burst from the faint ultra-compact binary candidate SLX 1737–282 as well as several short ones from the faint transient source GRS 1741.9–2853. We take these recent detections as an opportunity to briefly discuss our current observational and phenomenological understanding of these phenomena, with a particular emphasis on low accretion rate bursters.

1 X-ray bursts

An X-ray ray burster is a binary system consisting of a neutron star ($\sim 1.4\,M_\odot$) accreting matter from a low mass companion star ($< M_\odot$). The latter fills its Roche lobe and pours matter onto the neutron stars via an accretion disk, which accounts for most of the persistent X-ray flux of the source. On the surface of the neutron star, the accreted matter, mostly hydrogen and helium, reaches suitable temperature and pressure conditions for nuclear fusion. However these nuclear reactions are generally highly dependent on temperature and develop in a medium where the pressure is usually frozen either by quantum degeneracy or hydrostatic equilibrium. As a result, a slight increase of the temperature is not regulated by an expansion of the burning material, but instead enhances the fusion rate, which in turn increases the temperature and so forth, leading to a thermonuclear runaway (Mestel 1952, Schwarzschild & Härm 1965). This translates observationally in recurrent quick elevations of the count rate of the source, followed by exponential decays, called X-ray bursts. The duration of the decay is variable from bursts to bursts and has given rise to a classification in three categories: (i) *short bursts* lasting 10–100 s, separated by a few hours, (ii) *intermediate long bursts* lasting 10–20 min, separated by several weeks and *superbursts* lasting 1–3 h, separated by several months (fig.1 left).

1.1 Short bursts phenomenology

Short X-ray bursts were dicovered by Grindlay et al. (1976) and have been intensively studied over the last 30 years (see Lewin et al. 1993, Strohmayer & Bildsten 2006 and Galloway et al. 2008 for reviews). Early on, Fujimoto et al. (1981) showed that the nature of the nuclear fusion at stake in short X-ray bursts should be highly dependent on the accretion rate, $\dot{m}$, of the neutron star. Defining $x = \dot{m}/\dot{m}_{\rm Edd}$, where $\dot{m}_{\rm Edd}$ is the accretion at the Eddington luminosity, one classically distinguishes 5 different regimes:

1. $x \lesssim 10^{-6}$: Hydrogen (H) burns stably via pycnonuclear and thermonuclear (*pp*-process) reactions that do not depend strongly on temperature. So no X-ray bursts can be observed.

[1] AstroParticule & Cosmologie (APC) / Université Paris VII / CNRS / CEA / Observatoire de Paris – Bât. Condorcet, 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France.
[2] Service d'Astrophysique (SAp) / IRFU / DSM / CEA Saclay – Bât. 709, 91191 Gif-sur-Yvette Cedex, France.

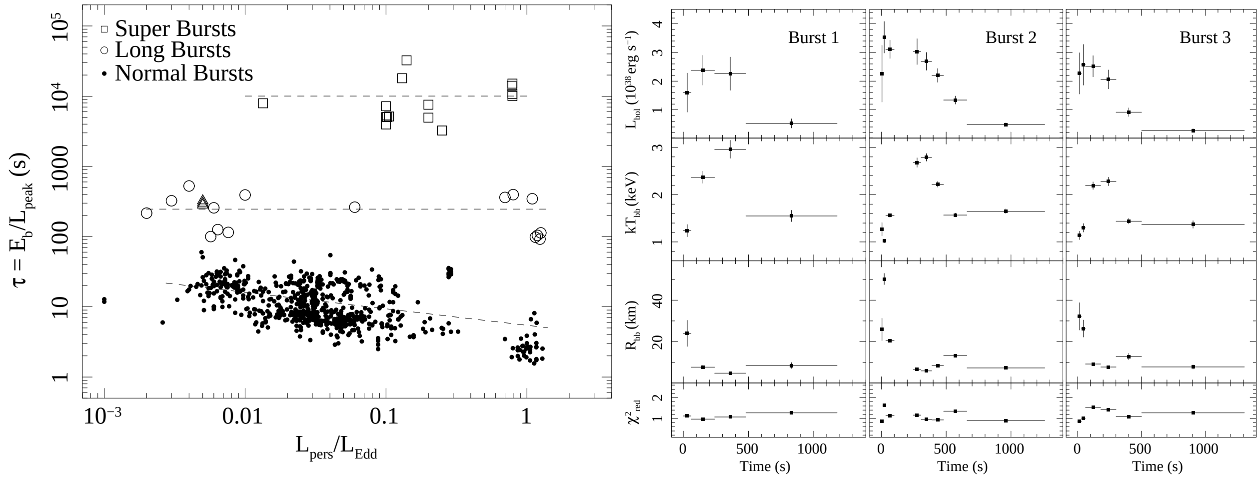

Fig. 1. Left : Duration of observed X-ray bursts as a function of persistent luminosity. **Right**: Spectral evolution of 3 intermediate long bursts from SLX 1737–282 recorded by *INTEGRAL*. The third panels clearly show the photospheric radius expansion of the neutron star. (Figures from Falanga et al. 2008).

2. $10^{-6} \lesssim x \lesssim 0.01$: H burns through the cold CNO cycle. The reaction rate is thus limited by proton captures, which depends a lot on temperature. H burning is then unstable and has two possible outcomes. If the column depth is high enough ($> 5 \times 10^7\,\mathrm{g\,cm^{-2}}$), the triple-$\alpha$ reaction can burn helium (He) unstably thus producing an He flash in a H-rich environment. Otherwise, a pure and weak H flash develops (only ~ 5 times the persistent luminosity) and sedimentation builds a thick pure He layer beneath the H burning shell (Peng et al. 2007, Cooper & Narayan 2007).

3. $0.01 \lesssim x \lesssim 0.1$: H burns into He via the hot CNO cycle, which is limited by β-decays independent of temperature. H burning is thus stable and heats the He layer building up underneath, until He ignites unstably beacause of the high temperature dependence of the triple-α reaction. One sees a powerful pure He flash, lasting only $\sim 10\,\mathrm{s}$. In general the energy release is so quick, due to the rapidity of strong interactions, that the burst reaches the Eddington luminosity. Consequently the atmosphere of the neutron star experiences a photo radius expansion (PRE).

4. $0.1 \lesssim x \lesssim 1$: H is piling up faster than it is depleted by steady burning, so that He ignites unstably in a H-rich environment. The flashes involve the *rp*-process to produce heavy elements and last longer ($\sim 100\,\mathrm{s}$), due to a series of slow β-decays governed by the weak interaction. Note that close to $x \sim 1$, He should start to burn stably between bursts, leading to "delayed mixed bursts" (Narayan & Heyl 2003).

5. $1 \lesssim x$: Temperature due to accretion is so high that both H and He burn steadily through hot CNO and stable triple-α reactions respectively. The bursting behavior thus completely stops.

1.2 Superburst and intermediate long bursts phenomenology

Superbursts are rare events, seen in sources which displays mainly short bursts. The basic scenario is that these short events produce heavy elements that settle down under the surface, in particular carbon, which detonates once in a while, producing a superburst. On the condition that the inner crust of the neutron star is hot enough, this model predicts recurrence times, energetics and durations in good agreement with the observations so far (Cumming & Bildsten 2001).

As for intermediate long bursts, recent theoretical developments have suggested that they should involve the burning of a thick layer of He. The first option is that the source has a low $\dot{m}$, so that we are in case 2 of paragraph 1.1. Weak H flashes produce a thick He layer that ignites when the proper column density is reached. The second possibility is that the companion star is a pure He donor, in an ultra-compact binary system for instance (see section 2.). Indeed, if $\dot{m}$ and the crustal heating are low enough, and in the absence of heating from hydrogen burning, then ignition of He can be delayed until a sufficiently thick layer of fuel has been accumulated. Though the burning of He is rapid, the cooling time is long (10–20 min) because of the thickness of the layer in which the heat is deposited (Cumming et al. 2006).

2 SLX 1737–282

SLX 1737–282 is a Galactic Center burster (fig.2 left) from which exclusively intermediate long bursts have been recorded so far. It is the only such source in the galaxy known to date. We recently reported the observations of 3 new long bursts (fig.1 right) from the source with the *INTEGRAL* satellite (Falanga et al. 2008). From the presence of PRE (fig.1 right, third panels) we are able to derive the source distance (7.3 kpc) and have evidence that the bursts resulted from He burning.

On the other hand, the estimated persistent bolometric luminosity of the source is rather low: $L_{\rm pers} \sim 0.005\,L_{\rm Edd}$. By working out the accretion column of the bursts and the expected recurrence time, we find that our observations of an apparent recurrence time of $\sim$ 86 days and burst energetics of $\sim 10^{41}$ erg, are in good agreement with pure He bursts. Yet, at this low $\dot{m}$ ($\sim 0.005\,\dot{m}_{\rm Edd}$) we should observe the presence of H in the flashes (see paragraph 1.1), unless the companion is a pure He star and no H can be accreted. As a matter of fact, we favor this latter explanation, as it is in line with the fact that SLX 1737–282 has recently been classified as an ultra-compact binary candidate (in't Zand et al. 2007). Indeed disk instability models of low mass X-ray binaries show that steady and low $\dot{m}$ systems must have short orbital periods ($P_{\rm orb} \lesssim 2\,$h), otherwise they would turn out to be transient (Dubus et al. 1999). Thus, as binaries evolution models demonstrate, SLX 1737–282 should be a system with a H-poor Roche lobe-filling companion (to persistently sustain the accretion), driven by gravitational radiation (for conservative mass transfer). This respectively sets contraints on the companion equation of state (fig.8 in Falanga et al. 2008) and the companion mass-orbital period plane (fig.9 in Falanga et al. 2008). As a result, we suggest that the companion star in SLX 1737–282 is likely to be a He white dwarf.

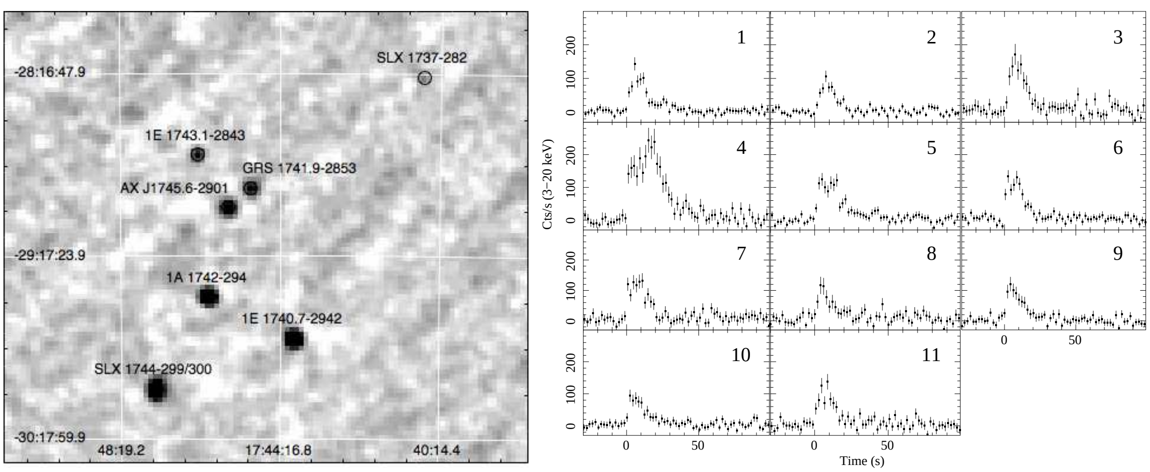

Fig. 2. Left : Mosaic of the Galactic Center in the 3–20 keV band, by the *INTEGRAL*/JEM-X1 module, from February to April 2007. The galactic plane runs from upper left to bottom right and the very center of the galaxy almost coincides with the low mass X-ray binary AX J1745.6–2901. **Right** : Short burts detected by *INTEGRAL*/JEM-X during the 2005 and 2007 outbursts of GRS 1741.9–2853.

3 GRS 1741.9–2853

GRS 1741.9–2853 is a faint transient burster from the Galactic Center (fig.2 left). In early 2007, a new outburst from the source has been followed by the *INTEGRAL* and *XMM-Newton* satellites. During this event, we have detected a total of 9 short X-ray bursts, 7 with *INTEGRAL*/JEM-X and 2 with *XMM-Newton*. By analysing archival data, we have also found 4 bursts with JEM-X during another outburst of GRS 1741.9–2853 in 2005 (see fig.2 right). From the brightest burst, we put an upper limit on the source distance at $\sim$ 8 kpc (Trap et al. 2008).

Interestingly, at the beginning and end of the outbursts, the source displayed bursts when its persistent luminosity was no bigger than $\sim 10^{36}\,{\rm erg\,s^{-1}} \sim 1\%\,L_{\rm Edd}$. This potentially makes GRS 1741.9–2853 an interesting probe of the low $\dot{m}$ burning regime (case 2, paragraph 1.1).

4 Conclusions and perspectives

SLX 1737–282 is the best example for which the observations convincingly match the theory of intermediate long bursts as being thermonuclear explosions of a thick He shell accreted from a pure He donor. A conclusive confirmation of this scenario would still be the detection of an optical modulation revealing a short period and so an ultra-compact nature.

More generally, with the systematic study of low $\dot{m}$ bursters, an interesting new field has started to emerge within the burst community (Cornelisse et al. 2004). There is now growing interest for the poorly studied nuclear regime in which H fusion is unstable. Theoretical work (Peng et al. 2007) has recently provided clues to bridge the gap between short and intermediate long burst, through unstable H burning. From an observational viewpoint, Boirin et al. (2007) put forward that unstable H burning may be responsible for bursts multiplets. These bursts at low accretion rates could even have some relevance in the mechanism of soft X-ray transients outbursts (Kuulkers et al. 2008). As we will argue in a forthcoming paper, a *transient* and *low accretion rate* burster like GRS 1741.9–2853 is an interesting target for further investigation of this burning regime.

References

Boirin, L., Keek, L., Mendez, M., et al. 2007, A&A, 465, 559

Cooper, R., & Narayan, R. 2007, ApJ, 661, 468

Cornelisse, R., in't Zand, J. J. M., Kuulkers, E., et al. 2004, Nucl. Phys. B, 132, 518

Cumming, A., & Bildsten, L. 2001, ApJ, 559, L127

Cumming, A., Macbeth, J., in't Zand, J. J. M., & Page, D. 2006, ApJ, 646, 429

Dubus, G., Lasota, J.-P., Hameury, J.-M., & Charles, P. 1999, MNRAS, 303, 139

Falanga, M., Chenevez, J., Cumming, A., et al. 2008, A&A, 484, 43

Fujimoto, M. Y., Hanawa, T., & Miyaji, S. 1981, ApJ, 247, 267

Galloway, D., Muno, M., Hartman, J. M., Psaltis, D., & Chakrabarty, D. 2008, arXiv:astro-ph/0608259v2

Grindlay, J., Gursky, H., Schnopper, H. et al. 1976, ApJ, 205, L127

in't Zand, J. J. M., Jonker, P. G. & Markwardt, C. B. 2007, ApJ, 465, 953

Kuulkers, E., in't Zand, J. J. M., & Lasota, J.-P. 2008 arXiv:astro-ph/0809.3323

Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1993, Space Sci. Rev., 193, 15

Mestel, L. 1952, MNRAS, 112, 598

Narayan, R., & Heyl, J. 2003, ApJ, 599, 419

Peng, F., Brown, E. F., & Truran, J. W. 2007, ApJ, 654, 1022

Schwarzschild, M., & Härm, R. 1965, ApJ, 142, 855

Strohmayer, T., & Bildsten, L. 2006, Compact Stellar X-ray Sources, ed. W. Lewin & M. van der Klis (Cambridge University Press)

Trap, G., Falanga, M., Goldwurm, A. et al. 2008, In prep.