Understanding superbursts

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Abstract

Superbursts were discovered at the beginning of this millennium. Just like type-I X-ray bursts, they are thought to be due to thermonuclear shell flashes on neutron stars, only igniting much deeper. With respect to type-I bursts, they last 10^3 times longer, are 10^3 as rare, ignite 10^3 times deeper (in column depth) and are thought to be fueled by carbon instead of hydrogen and helium. Observationally, they are sometimes hard to distinguish from intermediate duration bursts which are due to pure helium flashes on cold neutron stars. So far, 26 superbursts have been detected from 15 neutron stars in low-mass X-ray binaries that also exhibit type-I bursts. They are very difficult to catch and only 2 have been measured with highly sensitive instrumentation. Superbursts are sensitive probes of the neutron star crust and the accretion disk. The superburst phenomenon is not fully understood. Questions remain about the nature of the fuel, the collection of that fuel and the ignition conditions. The current state of affairs is reviewed and possible resolutions that lay ahead in the future discussed.

Key words: Stars: neutron – X-rays: bursts, binaries – Nuclear reactions

1. Introduction

Since 1969, 'type-I' X-ray bursts are being detected from space-borne observatories between roughly 1 and 10 keV (Belian et al. 1972; Grindlay et al. 1976; Matsuoka et al. 1980; Makishima et al. 1981; Gottwald et al. 1986; Lewin et al. 1993; Strohmayer & Bildsten 2006; Galloway et al. 2008). These bursts are due to thermonuclear shell flashes of hydrogen and helium in the freshly accreted upper layers of neutron stars in low-mass X-ray binaries (LMXBs; Hansen & van Horn 1975; Lamb & Lamb 1978; Wallace & Woosley 1981; Fujimoto et al. 1981), like those on white dwarfs are responsible for classical novae. The durations of most type-I bursts are between a few seconds and a few minutes. The time profile of the X-ray emission is typically a fast rise of duration a few seconds and an exponential-like decay. The shell flash occurs at large ($\gg 1$) optical but small linear depth (roughly 1 m) below the photosphere and temperatures may rise to order 1 GK. By the time the heat wave reaches the photosphere, the temperature is a few tens of MK and the typical peak energy of the photon spectrum is 5-10 keV. The flash itself lasts a fraction of second, although it may take a few seconds to engulf the whole neutron star. The burst decay phase essentially is the cooling of the neutron star and actually does not follow an exponential function but a power law (e.g., Cumming & Macbeth 2004; in 't Zand et al. 2014). The duration of the cooling is primarily set by the amount of mass that is heated up or, in other words, the column depth of the ignition (usually between 10^8 and 10^9 g cm^{-2}).

In the fall of 1996, the just launched two Wide Field Cameras (WFCs; Jager et al. 1997) onboard the Italian-Dutch BeppoSAX observatory (Boella et al. 1997) conducted a nine-day long observation of the Galactic center region. Thanks to the 40×40 square degrees field of view per camera, the WFCs could simultaneously observe about half the Galactic low-mass X-ray binary population. One of the LMXBs in the field of view was 4U 1735-44. Figure 1 shows the nine-day light curve resulting from that observation. It includes a remarkable feature on August 22, 1996: a fast rise exponential-like decay phenomenon with a duration of a few hours. Cornelisse et al. (2000) found this, and the spectrum, very reminiscent of a type-I burst except for the duration which is 10^3 as long. They proposed this as the longest thermonuclear burst ever observed. This marks the discovery of superbursts.

The discovery gave rise to searches in archival data from WFC and the All-Sky Monitor (ASM) on RXTE, which yielded 12 more very long bursts that were published between 2001 and 2004 (see Table 1). Wijnands (2001) introduced the term 'superburst'. Cumming & Bildsten (2001) and Strohmayer & Brown (2002) introduced the first explanation of the phenomenon as a thermonuclear shell flash fueled by carbon at a column depth $\sim 10^3$ times deeper than for type-I bursts.

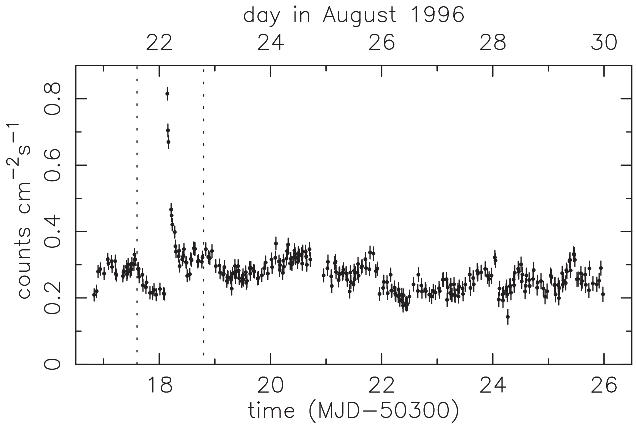

Fig. 1. Nine-day long light curve of 4U 1735-44 as observed with BeppoSAX-WFC, with the first detection of a superburst on August 22, 1996 (from Cornelisse et al. 2000)

In this paper, we briefly discuss the observational facts (§2.) and theoretical considerations (§3.) that define our current understanding of superbursts, summarize the importance of superburst research (§4.) and touch on future prospects (§5.).

2. Observational overview

2.1. Catalog & recurrence time

Table 1 presents a list of all 26 superbursts and their characteristics that have been reported up to January 2017. The most recent one is reported in these proceedings (Iwakiri et al. 2016a, see also Iwakiri et al. 2016b). It is from 4U 1705-44, a LMXB that was already predicted to be a superburster a decade ago (in 't Zand et al. 2003). The 26 superbursts are emitted by 15 low-mass X-ray binaries that are also emitters of type-I bursts. Currently, MAXI on the ISS is the most efficient superburst discovering machine. All six superbursts since 2011 were discovered with this device.

Five sources have exhibited multiple superbursts. They have high accretion rates except 4U 0614+09. The range of superburst recurrence times is between 10 d (for GX 17+2) to 10.5 yr (for 4U 1820-30). The average recurrence time is 4 yr, but this should be taken as an upper limit because there are data gaps. in 't Zand et al. (2003) perform a statistical analysis of the recurrence time and find 2 ± 1 yr. Keek et al. (2006) determine on a source-by-source basis and on the basis of the BeppoSAX-WFC database a lower limit to the recurrence time of usually 2 months. These determinations can probably be improved upon considerably with the much larger data sets that is now available through for instance INTEGRAL and MAXI.

2.2. Host binaries

While in the early years (2000-2004) host binaries of superbursts were all found to be LMXBs that are persistently accreting at a level of at least 0.1 times the Eddington limit, the picture changed as the data grew. There are now 4 transients among the 15 superbursters, and one system (SAX J1828.5-1037) with an unknown nature, but for certain with a low long-term average accretion rate like the 4 transients. Of the 7 host binaries with (tentatively) known orbital periods, 2 are ultracompact X-ray binaries (UCXBs), meaning that the composition of the donors, and therefore that on on the neutron star, is strongly deficient in hydrogen (4U 1820-30 and 4U 0614+09).

There are a number of prolific bursters that are semi-persistent and did not exhibit a superburst yet: 4U 1728-34, EXO 0748-676 (off since 2011), 4U 1702-429, 1E 1724.3045 (in Terzan 2), A 1742-294, 4U 1812-12, GS 1826-24 and Cyg X-2. While it is too early to derive a physical meaning of this, it is something to keep in mind. It may be related to the question of fuel accumulation for superbursts and ignition conditions. in 't Zand et al. (2003) did an investigation of the average α parameter among a number of persistent bursters. α is the ratio of the gravitational energy released by accretion since the last burst to the nuclear energy released through the present burst. It should be between about 30 and 200 (Lewin et al. 1993). in 't Zand et al. (2003) found a clear distinction between superbursters and non-superbursters. The former ones have a significantly higher α value ($\gtrsim 1000$).

2.3. Distinguishing superbursts from other long bursts

After the discovery of superbursts, another kind of thermonuclear X-ray burst was discovered that is also long but generally not as long as superbursts: intermediate duration bursts (in 't Zand et al. 2005; Cumming et al. 2006), the qualification *intermediate* referring to a duration between that of type-I bursts and superbursts (see Fig. 2). Since this may incur uncertainty in the identification of short superbursts, we discuss this somewhat more.

Most intermediate duration bursts are thought to result from the ignition of thick helium piles on cold neutron stars. Due to the low temperature, ignition is reached at higher pressure and larger column depths, and the helium needs much more time to reach ignition (days to weeks instead of hours) and bursts last longer. The thicker piles and the fast 3α helium-burning nuclear reaction will usually result in very high nuclear powers that easily surpass the Eddington limit and result in very strong photospheric expansion. The low temperatures go hand in hand with low accretion rates. All these circumstances are found in ultracompact X-ray binaries with orbital periods shorter than about one and a half hour

Table 1. Catalog of 26 superbursts from 15 sources, detected up to January 2017.

Source	Transient?	P_{orb} (min)	Date (Instr.)	Onset obs.?	Decay Time (hr)	L_{peak} (10^{38} erg s^{-1})	$\dot{M}$ (edd.)	Nearest burst (d)	y (10^{12} g cm^{-2})	E (10^{17} erg g^{-1})	Ref.[‡]
4U 0614+09		51?	2005-03-12(ASM)		2.1	> 0.1	< 0.01	-367/+19	0.2	5	1,a
			2014-11-03(MAXI)		5.2	2.8					2
4U 1254-69		236	1999-01-09(WFC)	y	6.0	0.4	0.13	-51/+125	2.7	1.5	3, 4, b
4U 1608-52	y		2005-05-05(ASM+HETE)	y	4.5	0.5	0.03	-57/+104	2.8	1.6	5
4U 1636-53		228	1996-06-19(ASM)		3.1	1.0		+96			6, c
			1997-07-13(ASM)		1.8	> 0.9		-122/+68			7
			1999-05-26(ASM)		2	0.8		-27/+15			8
			2001-02-22(PCA+ASM)	y	1.5	0.7		-2/+23	0.48	2.6	9, 4
4U 1705-44			2016-10-22(MAXI)		2.2	> 1.0					10
KS 1731-260	∼		1996-09-23(WFC)	y	2.7	1.4	0.1	-6/+34	1.0	1.9	11, 4
4U 1735-44		279	1996-08-22(WFC)		1.4	1.5	0.25	../+374	1.3	2.6	12, 4, d
GX 3+1			1998-06-09(ASM)		1.6	0.8	0.2	-62/+94			13
GX 17+2		10d?	1996-09-14(WFC)		1.9	1.0	1	+2			14, e
			1999-09-23(WFC)		1.0	1.3	1	+10	0.6	1.8	14
			1999-10-01(WFC)	y	0.7	1.7	1	+2			14, 4
			2000-09-08(WFC)	y	2.2	1.8	1	+12			14, 4
EXO 1745-248	y		2011-10-24(MAXI+BAT)		10	0.7	< 0.01		1.0	> 1	15, 16
SAX J1747.0-2853	y		2011-02-13(JEMX+MAXI)	y	4.2	3	0.1	-711/+25			17, 2
4U 1820-30		11	1999-09-09(PCA)	y	1	3.4	0.1	-168/+167	1	10	18, f
			2010-03-17(MAXI+ASM)*		0.5	> 3.3	0.15	+1549			19
Ser X-1			1997-02-28(WFC)		1.2	1.6	0.2	-162/+34	0.55	2.3	20, 4
			1999-08-09(ASM)		3.6	> 0.19	0.15	+309			7
			2008-10-14(ASM)		1.4	> 0.26	0.13	+55			7
			2011-12-06(MAXI)		2.3	0.9	0.21		2.1	4	10
SAX J1828.5-1037	?		2011-11-12(MAXI)		2.3	0.7	< 0.01				21
Aql X-1	y	1137	2013-07-20(MAXI)		4.3	1.0	0.1	+389			2, g

*According to Serino et al. (2016), this is not a superburst. It is listed here, because we believe that the alternative, it being an intermediate duration burst, is less likely given the high accretion rate. [‡]References (numeric for superburst data, alphabetical for orbital period): 1 - Kuulkers et al. (2010), 2- Serino et al. (2016), 3 - in 't Zand et al. (2003), 4 - Cumming & Macbeth (2004), 5 - Keek et al. (2008), 6 - Wijnands (2001), 7 - Kuulkers (2009), 8 - Kuulkers et al. (2004), 9 - Strohmayer & Markwardt (2002), 10 - Iwakiri et al. (2016a), 11 - Kuulkers et al. (2002), 12 - Cornelisse et al. (2000), 13 - Kuulkers (2002), 14 - in 't Zand et al. (2004), 15 - Altamirano et al. (2012), 16 - Serino et al. (2012), 17 - Chenevez et al. (2011), 18 - Strohmayer & Brown (2002), 19 - in 't Zand et al. (2011), 20 - Cornelisse et al. (2002), 21 - Asada et al. (2011), a - Shahbaz et al. (2008), b - Motch et al. (1987), c - van Paradijs et al. (1990), d - Corbet et al. (1986), e - Bandyopadhyay et al. (2002), f - Priedhorsky et al. (1986), g - Chevalier & Ilovaisky (1991)

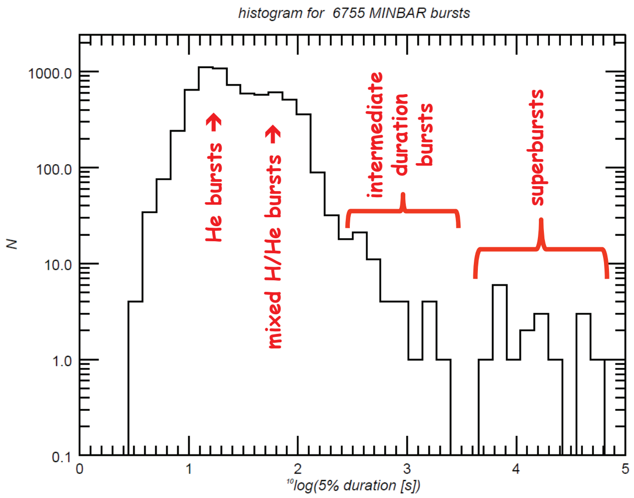

Fig. 2. Preliminary histogram of burst durations as determined from bursts in the MINBAR archive (Galloway et al., in prep.)

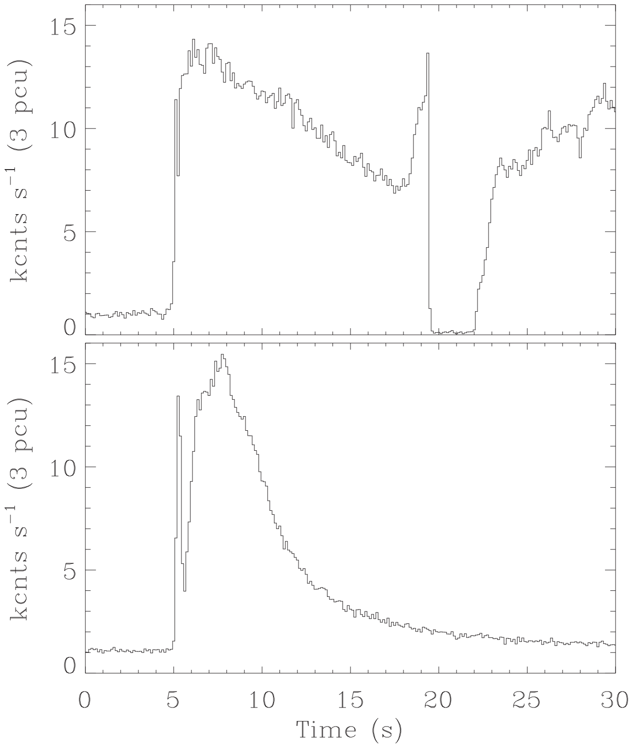

Fig. 3. PCA-measured light curves of two bursts from 4U 1820-30. Top panel: first 30 s of the superburst. Bottom panel: a type-I burst from the same source. From Strohmayer & Brown (2002).

(Nelson et al. 1986) and that is indeed what observations show (in 't Zand et al. 2007; in 't Zand & Weinberg 2010).

Peng et al. (2007) predict a small regime in accretion rate of H-rich systems ($\approx$ 0.003 times Eddington) where also long helium bursts can happen after long series of pure H bursts. However, this is a very small range of allowed accretion rates and pure H-bursts have never been detected yet. Nevertheless, there are sporadic reports of intermediate duration bursts from H-rich systems (Degenaar et al. 2010; Chenevez et al. 2007).

Identifying superbursts, particularly when data coverage is sporadic, can be cumbersome. One should, for instance, be careful about long bursts that are discovered from UCXBs at low mass accretion rates. These may be intermediate duration bursts. In fact, in a few cases superburst detections had to be revised, see the careful evaluation by Serino et al. (2016) . Furthermore, in my opinion this qualifies the identifications as superbursts in 4U 0614+09 and SAX J1818-1036 as less certain (see also Kuulkers et al. 2010 for 4U 0614+09).

2.4. Peak luminosities

Roughly 20% of type-I bursts have peak luminosities near the Eddington limit (Galloway et al. 2008): 2.0×10^{38} erg s^{-1} for H-rich atmospheres and $3.4{\times}10^{38}$ erg s^{-1} for H-poor atmospheres. The situation is different for superbursts. All superbursts except the PCA one from 4U 1820-30 (Strohmayer & Brown 2002) and possible the JEM-X burst of SAX J1747.0-2853 (Chenevez et al. 2011) are sub-Eddington. This immediately shows that the fuel layer is not burning completely.

2.5. Precursors

Most superbursts are discovered with low duty-cycle instruments, particularly the ASM on RXTE and MAXI on the ISS. These devices observe more than 80% of the sky every 90-min satellite orbit, but only for about 1 min. Therefore, it is easy to detect superbursts because they generally last longer than 90-min, but it is also difficult to catch the onset of superbursts. The onset has been observed in 8 of the 26 superbursts. Interestingly, in each of these cases the onset is marked by a short burst. This is often called a precursor, but actually there is only one case (the PCA superburst of 4U 1820-30) where there is truly a brief period without burst emission between the precursor and the main burst.

Figure 3 shows the onsets of a superburst and an ordinary burst from 4U 1820-30, detected with the high-throughput PCA. The superburst onset is characterized by the precursor (from 5-18 s) and the superburst (starting at 18 s), and the dips in both these bursts. The dip in the precursor is very short (less than the time resolution of $\frac{1}{8}$ s) and possibly not complete to the pre-burst flux level. The dip in the superburst drops to below the pre-burst level. Both of these dips are consistent with photospheric expansion (Lewin et al. 1984) with adiabatic cooling, whereby the cooling in the second dip is so strong that the X-ray signal is lost (Keek 2012). The drop to below the pre-burst level is due to the photosphere covering up the X-ray emitting part of the accretion disk (e.g., in 't Zand & Weinberg 2010).

Alternatively, Weinberg & Bildsten (2007) attribute the first brief dip as a pause between a spike due to a shock breakout and a prematurely ignited type-I pure-helium burst. However, Keek & Heger (2011) found that the heat released by the fallback of the photosphere after the shock breakout may be sufficient to ignite the type-I burst and that this occurs on time scales much shorter (10^{-5} s) than the dip time scale. After analyzing the spectral evolution during the dip, Keek (2012) concluded that it could be attributed to photospheric expansion. Keek (2012) also found that the precursor is more energetic than ordinary type-I bursts and, therefore, cannot be powered solely by the burning of accreted helium. They attribute the additional energy to the shock heating, supporting numerical models that predict that superbursts result in a detonation (Weinberg et al. 2006) and shock that generates enough heat or overpressure to power the precursor. A similar onset is observed in the other superburst detected with the PCA.

2.6. Burst quenching

Some superbursters are prolific emitters of type-I bursts at the time of the superburst, with recurrence times of merely a few hours. These include KS 1731-26 and 4U 1636-536. But it is noticeable that this emission of type-I bursts is quenched for a considerable period of time after the superburst (Kuulkers et al. 2002; Cornelisse et al. 2002), namely about one month. Apparently, the superburst influences the nuclear burning for a considerably longer time than when its emission is visible.

Measuring the duration of burst quenching is difficult. One needs a substantially high duty cycle to detect type-I bursts. This is not easily accessible with regular all-sky monitors. Quench time measurements are very interesting, though. They provide a clean means to observe the transition between stable and unstable nuclear burning (see Keek et al. 2012).

3. Theory

As with type-I bursts, the general picture is clear of how superbursts come about (a deep thermonuclear shell flash), but there are two essential issues that need resolution.

3.1. Inferring basic physics parameters

Cumming & Macbeth (2004) and Cumming et al. 2006 showed that it is possible to infer from the light curve, in particular the peak luminosity and the decay profile, the ignition column depth $y_{12} = y/10^{12}$ g cm^{-2} and energy yield $E_{17} = E/10^{17}$ erg g^{-1} of the heated matter. The higher the energy yield is, the higher the peak luminosity (up to the Eddington limit). The deeper the ignition is, the longer the duration. An example of a fitted superburst decay is shown in Fig. 4. Table 1 shows the values of these two parameters for many superbursts. Due to the lack of onset coverage, it is often difficult to obtain reasonable constraints on y_{12} and E_{17}, particularly the latter. Therefore, these numbers lack in many cases.

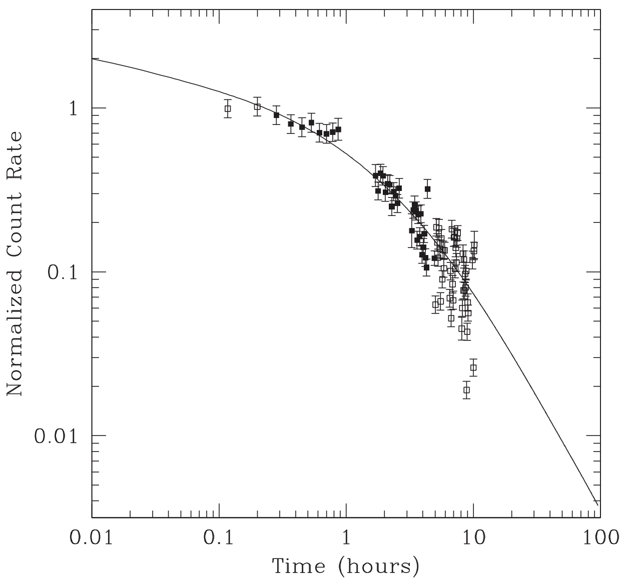

Fig. 4. The decay of the superburst from 4U 1735-44 (see Fig. 1 fitted with a model parametrized with y_{12} and E_{17} (see text and Table 1). From Cumming et al. (2006).

Keek et al. (2015) improved the light curve diagnostic power by including the slope of the temperature relation with depth as a free parameter. This impacts in particular the rise phase of the light curve.

The expected values for CNO burning and 3α process are $E_{17} = 64$ and 15, respectively. This is 1 to 2 orders of magnitude larger than the observed values for superbursts. The energy yield for nuclear burning of carbon to iron-group elements is about 10. The superburst from 4U 1820-30 has the very same value.

3.2. What fuel is burning?

The longer duration points to a deeper ignition, a higher density and a higher temperature than for type-I bursts. This makes it easier to overcome the Coulomb barrier of heavier elements than hydrogen and helium. The next most abundant element, certainly after the burning of hydrogen to helium through the CNO cycle and the burning of helium through the 3α process, seems carbon and this is the fuel that was considered by Strohmayer & Brown (2002) and Cumming & Bildsten (2001).

The E_{17} values are more or less consistent with carbon burning. They range between 1.5 and 10. This implies mass fractions of burnt carbon between 15 and 100%. Part of the remaining composition are the heavy isotopes needed for the right ignition depth (Cumming & Bildsten 2001) and whose photo-disintegration, furthermore, might contribute up to half the superburst energy, possibly lowering the required carbon in the fuel (Schatz et al. 2003).

3.3. Issue 1: how to obtain and maintain enough fuel?

If temperature becomes too high, the Coulomb barrier of carbon atoms is easier overcome by ambient protons and alpha particles through the reactions ^{12}C(p,γ)^{13}N and ^{12}C(α,γ)^{16}O, thus destroying the carbon. This can easily happen during helium flashes since the carbon and helium are in the same layer. Thus, helium flashes are responsible for both the production and destruction of carbon. Generally, it is thought that the only manner in which carbon destruction can be prevented is by preventing temperature to grow too large during 3α burning. This is only possible during stable helium burning. There is observational evidence for that, through the measurements of the burst α parameter (see §2.2.). Also theoretically, improvements are made in the understanding. Stevens et al. (2014) proposes that the rp-process consumes all protons before they get a chance to capture on carbon. Keek & Heger (2016) introduces a new regime of stable hydrogen burning that increases the temperature in the H-depleted layer underneath somewhat, yielding higher 3α rates without going runaway.

3.4. Issue 2: how to ignite the fuel?

For diluted carbon mixtures, as suggested by the E_{17} values, it is difficult to reach ignition conditions. The temperature at a depth of $y_{12} \approx 1$ is simply not high enough to overcome the Coulomb barrier. This temperature is primarily set by a heat flow from the crust, where pycnonuclear reactions and electron captures provide a heat source of $Q_b = 0.1 - 0.6$ MeV/nucleon. The power scales with the accretion rate. Cumming & Bildsten (2001) initially resolved this issue by proposing reduced conductivity of the ignition layer, thus reducing the cooling of the layer. Then the crustal heating may be enough to reach ignition temperatures, provided the mass accretion rate is in excess of 0.1 times Eddington.

However, two recent findings aggravate the issue again. First, the detection of superbursts from transient accretors, starting with 4U 1608-52 (Keek et al. 2008) and with an extreme case of EXO 1745-248 (Serino et al. 2012; Altamirano et al. 2012). The accretion rate, averaged over the superburst recurrence time, is (much) lower for transients so that crustal heating is accordingly weaker. Second, recent calculations of neutrino cooling through the URCA process in the crust (Schatz et al. 2014) and the deep ocean (Deibel et al. 2016) show it to be much more efficient than previously thought.

The solution may come from finding shallow heating processes, for instance due to rotational mixing and thus deeper CNO burning (Keek et al. 2009) or freeze out of heavy elements at the bottom of the ocean that induces convection which heats up the superburst layer (Medin & Cumming 2011), but as yet the issue of unreachable carbon ignition conditions remains.

4. Why study superbursts?

As may be clear from above, studying superbursts is interesting in its own right, but it is also very useful for addressing a wide variety of scientific questions, for instance: 1) They are related to the same nuclear process (explosive carbon burning) that is thought to be responsible for type Ia supernovae. Understanding the ignition will improve our understanding of type Ia SN ignition; 2) Since the ignition is close to the neutron star crust, superburst characteristics depend on the thermal properties of the outer crust and, thus, provide a diagnostic of that crust (e.g., Cumming et al. 2006); 3) Superbursts are sensitive probes of the neutron star spin and binary orbit, through the detection of transient ms oscillations during superbursts (Strohmayer & Markwardt 2002); 4) Superbursts can be used as seismology probes of the neutron star interior, through the detection of oscillations other than due to the spin (Strohmayer & Mahmoodifar 2014); 5) Superbursts can be used as probes of the accretion disk. They irradiate and heat up the accretion disk which can be observed through reflection features in the superburst spectrum (e.g., Ballantyne & Strohmayer 2004; Keek et al. 2014). This irradiation happens by a simple spectral shape (black body) and over a broad range of tractable temperatures; 6) The cooling of the neutron star envelope after a superburst has an observationally convenient time scale (days) to relatively easy probe ignition conditions of hydrogen and helium burning (Keek et al. 2012).

5. Future

Only 11 superbursts have an observational coverage that is better than 10%, strongly affecting measurements of peak luminosities, quench times and onset profiles. Only 2 superbursts have been observed with an effective area of significantly more than $\sim$100 cm^2, strongly affecting sensitive measurements of the spectrum (e.g., Keek et al. 2014) and interesting variability such as burst oscillations (Strohmayer & Markwardt 2002). Although MAXI and other instruments are very useful in constraining superburst recurrence times and ignition depths, it is obvious that much is to be gained from measurements with higher duty cycles and larger sensitivity. This may be obtained through 1) all-sky monitors that have large sky coverage and reasonable effective area $\gtrsim 100$ cm^2 in the 1-10 keV band and 2) large X-ray telescopes with quick read-out times that spend substantial amounts of observing time on the population of potential superbursters (bursters with high α values) or can be quickly brought on target after the onset of a superburst. One concept platform where both of these types of instruments/observations are foreseen in a optimum manner is LOFT (e.g., Feroci et al. 2016; in 't Zand et al. 2015), with spin off concepts eXTP (Zhang et al. 2016) and Strobe-X (Wilson-Hodge et al. 2017). In the mean time, Astrosat (Agrawal 2006) and NICER (Gendreau et al. 2012) are and will be valuable assets in the study of superbursts if caught (see also Keek et al. 2016).

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