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Simulation of X-Ray Bursts and Superbursts

Julia Reichert[1], Sofie Fehlmann[1], Rubén Cabezón[1] and Friedrich-Karl Thielemann[1]

[1]*Departement für Physik, CH-4056 Basel, Switzerland*

E-mail: julia.reichert@unibas.ch

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Regular bursts have been observed in binary systems containing a neutron star with an accretion flow of matter from the companion star. These bursts are so-called type I X-ray bursts and occur due to thermonuclear explosions in the accreted shell of the neutron stars. Observations have shown that after thousands of X-ray bursts a rare superburst event may take place. These superbursts are thought to be triggered by unstable carbon ignition from the accumulated ashes of the previous X-ray bursts. One of our aims is to produce a self-consistent superburst, for which the amount of the remaining ^{12}C in the ashes is a crucial factor. Furthermore, we investigate the influence of the crustal heating on the behaviour of X-ray bursts and on the composition of their ashes.

KEYWORDS: X-ray burst, 1D simulations, Superburst

1. Introduction

In the last 40 years, thousands of X-ray bursts have been observed (for an observational overview see [1]) These observations are an important source of information about neutron stars. The profile of an X-ray burst (Fig. 1) has typically the shape of a fast rise and an exponential decay [2]. X-ray bursts show recurrence times of hours or days. A rarer event is the superburst (Fig. 2), which differs from a usual X-ray burst in shape, energy release, duration and recurrence time, amongst other characteristics [3, 4]. There are only a few detections of superbursts until now.

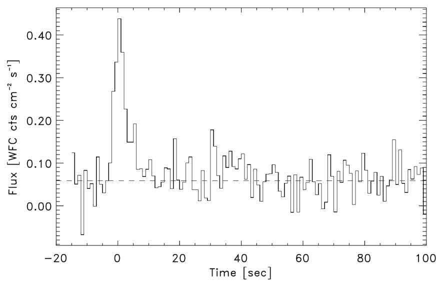

Fig. 1. Type I X-ray Burst [5]

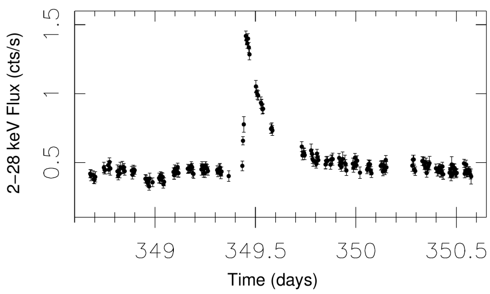

Fig. 2. Superburst [6]

In a neutron star binary system, hydrogen and helium-rich matter from the envelope of a companion star is transferred over Roche lobe overflow onto the surface of a neutron star. X-ray bursts are thought to stem from explosive hydrogen and/or helium burning of the accreted matter due to compression and the high temperature [7–9]. The explosive burning stops either when the matter is not degenerated anymore, H is exhausted or the end-point of the rp-process is reached [10]. After approximately a thousand Type I X-ray bursts a superburst can occur, which is thought to originate from explosive carbon burning of the accumulated ashes of the previous X-ray bursts [11, 12]. Current simulations of X-ray bursts have the problem of not being able to build up a surviving fraction of ^{12}C needed for triggering the superburst [10]. Therefore, we investigate the influence of important parameters like crustal heating, accretion rate and composition of the accreted matter, on the distribution of the ashes, the light curve and other observables.

2. Simulation

To simulate X-ray bursts we use an implicit 1D scheme [13] (Fig. 3) where the general relativistic hydrodynamic code AGILE [14] is coupled with a nuclear reaction network solver [15]. Type I X-ray bursts are assumed to take place in the atmosphere (Fig. 4) where the density ($\rho = 10^6$ g/cm^3) fulfills the condition for hydrogen and helium ignition. Our computational domain starts at the photosphere of the neutron star and goes down to the ocean, at a column density up to 10^{13} g/cm^2, which corresponds to the condition of the outer crust of the neutron star. In our simulations we accrete matter with solar composition. Superbursts are assumed to ignite at the column density of 10^{12} g/cm^2 ($\sim \rho = 10^8 - 10^9$ g/cm^3, see [16]).

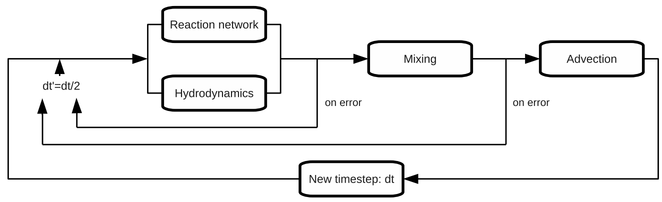

Fig. 3. Schematic view of calculation procedure [17]

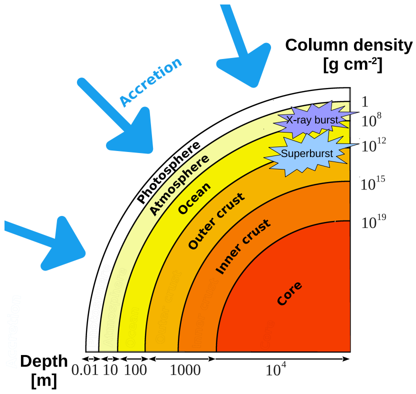

Fig. 4. Shell model of a neutron star [17]

3. Varying Crustal Heating

Former works (e.g. [18]) show that an additional crustal heating should favour a successful superburst ignition. We run simulations varying the crustal heating from 0.6 MeV/nuc up to 1.5 MeV/nuc in steps of 0.1 MeV/nuc for accreting matter with solar composition at a constant accretion rate of 10^{17} g/s. For a crustal heating of 0.6 MeV/nuc we get uniform bursts (Fig. 5). Increasing the crustal

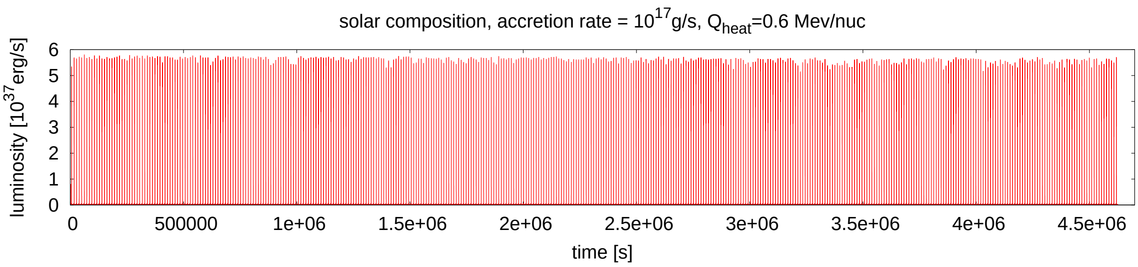

Fig. 5. 420 Type I X-ray bursts with 0.6 MeV/nuc of crustal heating and 10^{17} g/s accretion rate of matter with solar composition.

heating leads to increasingly irregular bursts. In the case of 1.0 MeV/nuc (Fig. 6) the peak luminosity changes from $5 \cdot 10^{37}$ erg/s up to $6 \cdot 10^{37}$ erg/s and the recurrence time grows from 2.8 h up to 3.4 h. After this abrupt change the bursts become more uniform. If the crustal heating exceeds 1.3 Mev/nuc we get stable burning after roughly 100 bursts (Fig. 7). For a successful ignition of a superburst it is believed that one needs a mass fraction of carbon of over 0.1 which is illustrated by the magenta colored line in Figures 8 and 9. As we can see in these two figures, an increase of the crustal heating favours the production of carbon in the ashes of the X-ray bursts but too high crustal heating leads to stable burning. From these results we conclude that there is a favored range for the value of the crustal heating that is suited for building up the ^{12}C in order to produce a superburst.

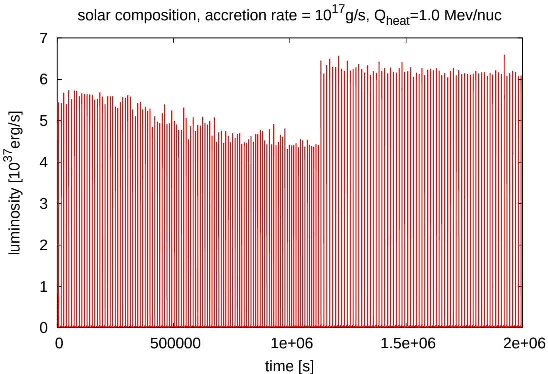

Fig. 6. 191 Type I XRBs with 1.0 MeV/nuc of crustal heating.

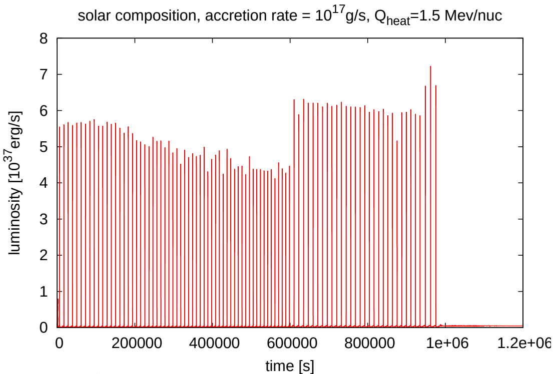

Fig. 7. Stable burning after ~100 XRBs with 1.5 MeV/nuc of crustal heating.

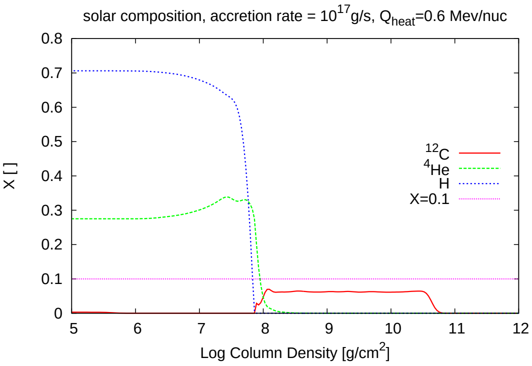

Fig. 8. The mass fraction of C, He and H for the case of 0.6 MeV/nuc after 420 bursts.

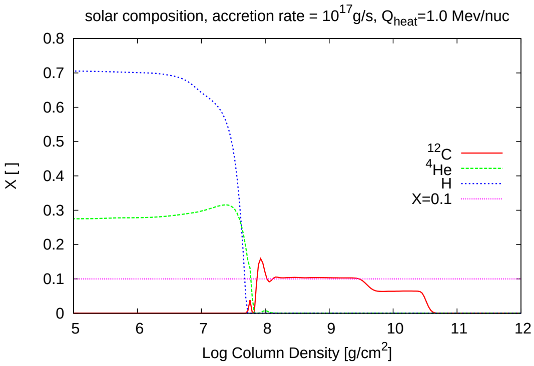

Fig. 9. The mass fraction of C, He and H for the case of 1.0 MeV/nuc after 191 bursts.

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