Superburst models for neutron stars with hydrogen and helium-rich atmospheres

Neutron stars are extremely compact stars. On their surface gravity is over a hundred billion times stronger than on Earth. In a binary star system hydrogen and helium from the outer layers of the companion star can be transferred to the surface of the neutron star. There it is quickly compressed by the strong gravity until explosive nuclear fusion ignites. All the hydrogen and helium burn in a few seconds, resulting in a short powerful burst of X-rays. These bursts occur as often as every few hours, and are observed from close to 100 neutron stars in our Galaxy.
The ashes of hydrogen and helium fusion pile up. After approximately a year the carbon in the ashes is compressed sufficiently to start burning explosively. This powers an exceptionally energetic X-ray burst that lasts as long as a day: a superburst. The superburst heats the surface such that freshly accreted hydrogen and helium does not burn in bursts, but burns continuously. Bursts are quenched and return only when the surface has cooled down.

Using multi-zone numerical simulations that include a large adaptive network of nuclear reactions, we investigate how the nuclear burning processes of hydrogen and helium at the surface change under the influence of a superburst igniting in a deeper layer. We construct the model by accumulating a carbon-rich mixture that represents the fuel composition for superbursts. Half a day before carbon ignites we replace the accretion composition by hydrogen and helium-rich material. Several short hydrogen/helium bursts occur (Fig. 1 left). As soon as the superburst ignites, bursts are quenched as hydrogen and helium burn stably (Fig. 1 center). After the surface has cooled for a day, the burning behavior changes. First burning is marginally stable, producing oscillations in the luminosity. During a brief time oscillations and small bursts alternate, until only bursts remain (Fig. 2). Over the course of a month the bursts become brighter and the recurrence times longer, returning to the values from before the superburst. This is the first time the transitions between the different burning regimes have been modeled self-consistently in such detail.

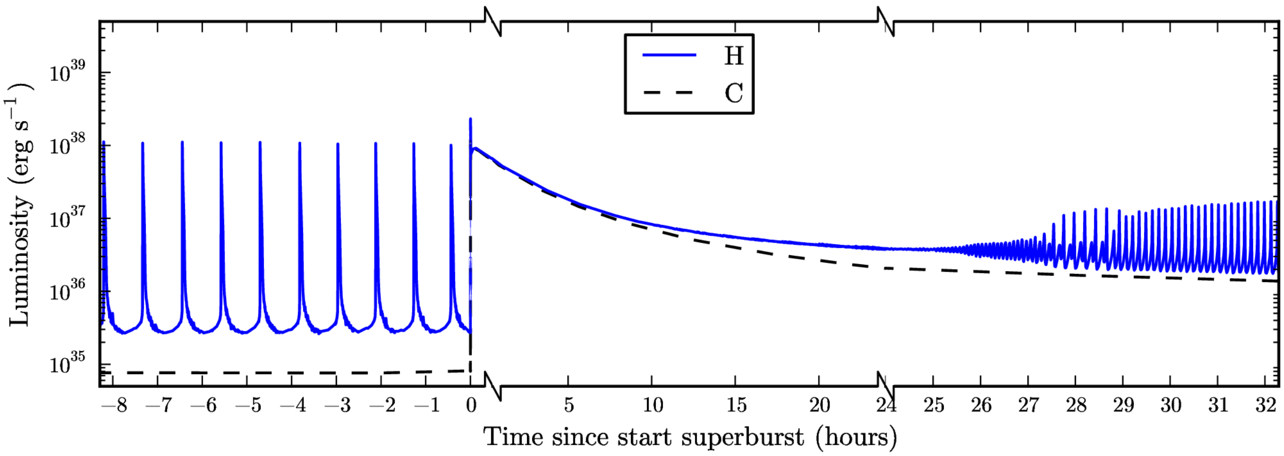

Fig. 1 Luminosity from the neutron star surface over time. Hydrogen and helium burning in short bursts is interrupted by a superburst from carbon burning. When the surface cools down bursts return.

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Previous models assumed helium burning through the triple-alpha process to be the dominant nuclear reaction, and predicted a burst quenching period of close to a week. In recent years JINA researchers found that the ignition of bursts is not just determined by one process, but rather by the complex interplay between both hydrogen and helium burning processes: the triple-alpha process, the hot CNO cycle, and the break out reactions from the latter. In our models this results in a much earlier return after a quenching period of only one day.

Observations of superbursts are scarce, and the return of bursts afterwards has not been detected. We use the large MINBAR catalog of burst observations to find the strongest constraints on burst quenching so-far. It is interesting to note that the changes in burst behavior that we predict have recently been observed in a different context from the remarkable transient source IGR J17480-2446.

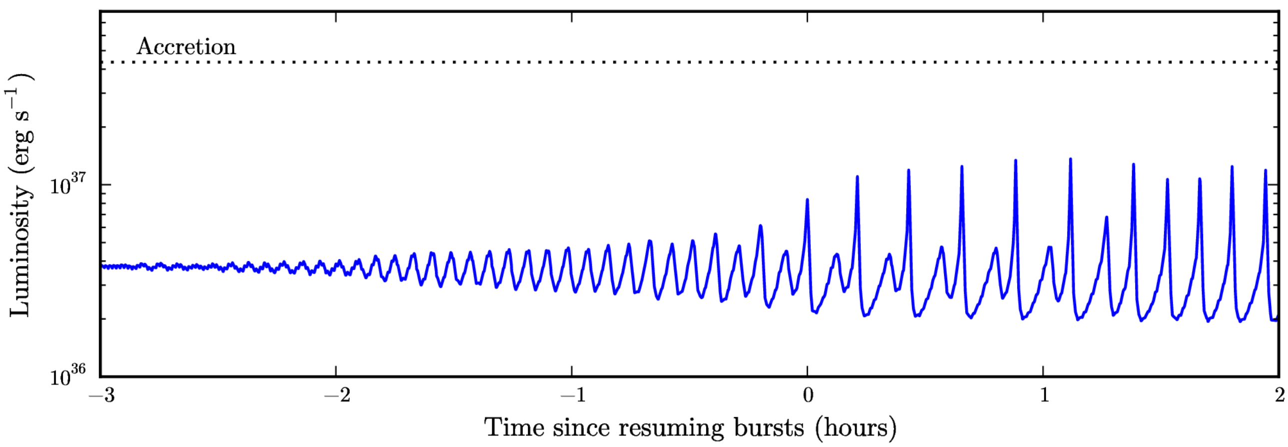

Fig. 2 Zoom-in of the return of bursts. First hydrogen and helium burning is oscillatory. Slowly it transitions into weak bursts. During a short time oscillations and bursts alternate.

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