# Multi-Zone Models of Superbursts from Accreting Neutron Stars

Neutron stars are the compact remnants of massive stars. In a binary star system, they can accrete hydrogen and helium-rich material from a companion star. Due to the high surface gravity, thermonuclear reactions take place in the thin neutron star envelope, creating carbon and heavier elements.

After approximately one year, the bottom of the accreted layer reaches the conditions for explosive carbon burning at a depth of 100m. This is close to the crust (a solid layer), which means that the ignition depends on crustal heating. The runaway carbon burning results in a bright day-long burst of X-rays: a superburst. Observations and models of superbursts constrain the heating by nuclear reactions of neutron-rich isotopes in the crust. Superbursts are, however, rare: only 18 have been observed from 10 sources, whereas thousands of hydrogen/helium flashes have been detected from 90 neutron stars in our Galaxy.

We create one-dimensional multi-zone models of the neutron star envelope by building up a carbon-rich layer at a rate typical for superbursting neutron stars, assuming various values for the amount of heat from the crust. We follow the nuclear reactions during the superburst, as well as the cooling. We obtain a light curve with the same characteristics as the observations: a bright precursor burst at the start, and a decay that lasts hours (Fig. 1). The carbon burning starts as a detonation at the bottom of our model, close to the crust (Fig. 2). This generates a shock that travels towards the surface, where it produces a very short shock break-out peak in the X-ray light curve. The shock causes the outer layers to expand. They fall back on a time scale of tens of microseconds and release the bulk of the energy deposited by the shock. This produces a bright peak in the light curve that may correspond to the observed precursor burst before superbursts. On a longer time scale after the precursor, the heat from carbon burning diffuses to the surface, producing the actual superburst. It takes up to a day for the surface to cool down, and the superburst X-ray emission to disappear.

These are the first multi-zone models of recurring superbursts, where the accumulation of the fuel layer is followed. The simulated light curves reproduce all the observed characteristics, including the precursor burst, which we attribute to the fall-back of shock-expanded layers. To exactly reproduce observed superburst light curves, however, the models require a higher mass accretion rate than what is inferred from observations. This inconsistency prevents us from using the models to pose stringent constraints on the crustal heating by nuclear processes.

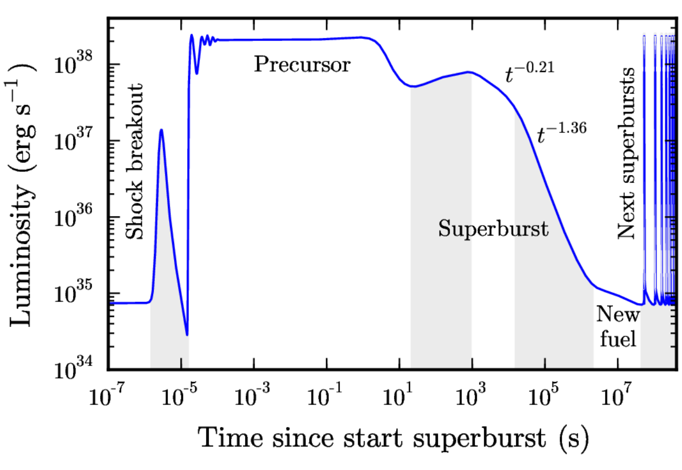


*Fig. 1 Simulated light curve of a superburst. We indicate the different phases of the superburst. Several followup superbursts are shown.*

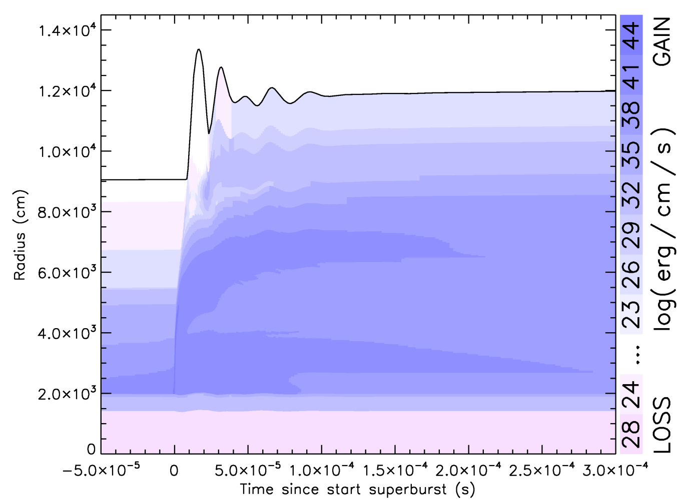


*Fig. 2 The onset of a superburst on a very short time scale: energy generation/loss (color scale) in the neutron star envelope. Carbon ignition starts at the bottom and drives a shock to the surface, which expands, falls back and oscillates for some time.*

Laurens Keek & Alexander Heger University of Minnesota
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