Oscillating Burning on Accreting Neutron Stars

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Low mass x-ray binaries, in which a neutron star or black hole accretes from a low mass companion star, exhibit a range of periodic and quasiperiodic phenomena, ranging from very low frequency (mHz) noise to kHz quasiperiodic oscillations (QPOs). This variability has mostly been associated with material orbiting in the accretion flow close to the compact object. In the case of a neutron star accretor, an important question is whether any of these phenomena originate from, or are associated with, the neutron star surface. This could allow us to identify the compact object as a neutron star or a black hole, as well as offering a probe of the neutron star surface layers. Unstable nuclear burning on neutron star surfaces has been known for a long time, and is observed as Type I x-ray bursts. Not all accreting neutron stars, however, show Type I x-ray bursts.

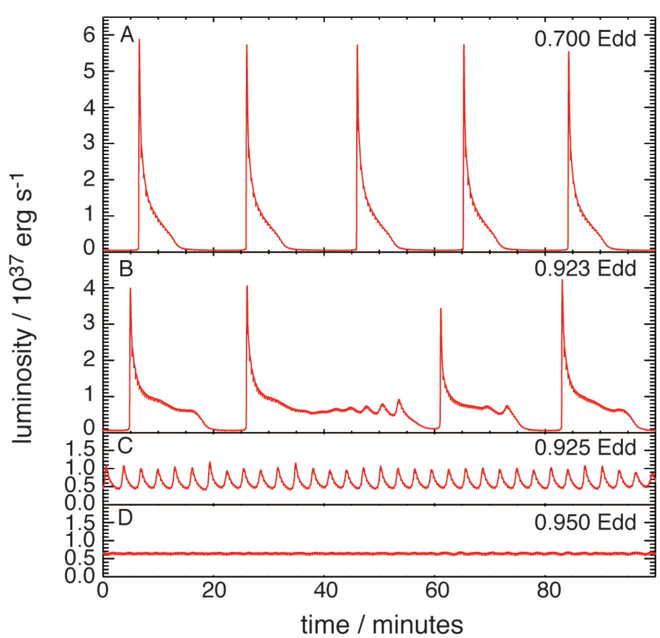

Fig. 1.
Light curves for different accretion rates (upper right corner gives accretion rate in units of Eddington accretion rate). Panel A shows regular bursting with stable recurrence times. Panel B shows weaker bursts with a partial oscillatory behavior in the tail of the burst light curves. Panel C shows oscillatory rather behavior and no bursts. Panel D shows very small oscillations, essentially stable behavior.

Revnivtsev et al. [1] discovered a new class of mHz QPOs in three Atoll sources, 4U 1608-52, 4U 1636-54, and Aql X-1, which they proposed were due to a special mode of nuclear burning on the neutron star surface. These mHz QPOs have frequencies in the range 7–9 mHz (timescales of ~ 2 min). The centroid frequency of the mHz QPO was stable on year timescales in a given source, and the same to within tens of per cent in all three sources in which it was detected. In 4U 1608-52, a transient source whose luminosity is observed to change by orders of magnitude, the mHz QPO was only present within a narrow range of luminosity, $L_X \approx 0.5$–1.5 times 10^{37} rm erg s^{-1}. This luminosity marks a transition from frequent Type I x-ray bursting at low accretion rates to the disappearance of Type I x-ray bursts at high accretion rates, a transition that is common to many x-ray bursters.

We model this transition of behavior from Type I x-ray bursting to stable burning and find the occurrence of MHz QPOs at the transition accretion rate ([2], Fig. 1). The calculations are done using an implicit one-dimensional hydro code that includes the energy release from nuclear burning and follow the nuclear reactions on some 1000 isotopes. Figure 2 shows the band of nuclear energy generation (blue) below the surface (black), the oscillations in nuclear energy release and the corresponding variations of the emitted radiation. In Fig. 3 we show in more detail the structure of the burning surface layer of the neutron stars at four different phases during an oscillation. This is the same model as shown in Fig. 2, Panel C. The white and gray stripes correspond to one cycle of oscillation each, with the interfaces corresponding to the time of a maximum in the light curve at the time of the accretion of that layer. The small inserts at the upper right corners indicate the position in the light curve (red) cycle of the snapshot (black dot; intensionally aligned with a layer interface). Note that the decreases of some of the radioactive isotopes in the right-hand side of the figure are due to their radioactive decay.

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[1] M. Revnivtsev, et al., *A&A* **372**, 138 (2001).
[2] A. Heger, et al., "Millihertz Quasi-Periodic Oscillations from Marginally Stable Nuclear Burning on an Accreting Neutron Star," Los Alamos National Laboratory report LA-UR-05-8083 (2006); *Astrophys. J.*, accepted, 2006; arXiv:astro-ph/0511292.

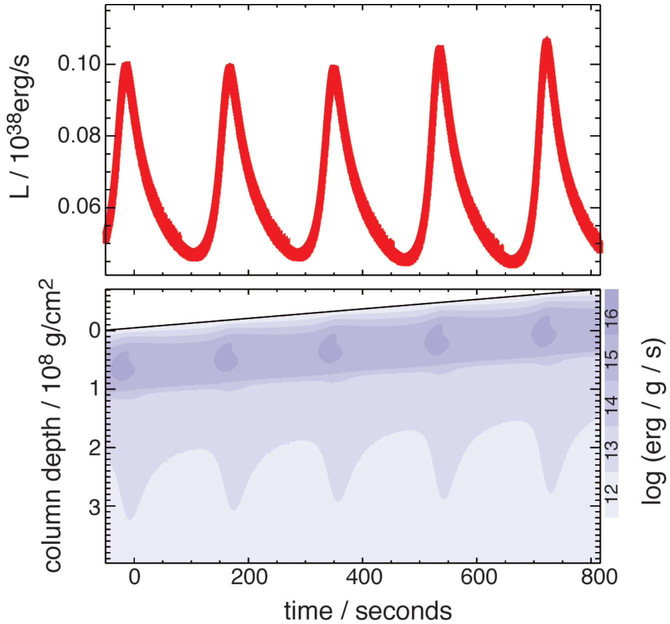

Fig. 2.
Detailed light curve (upper panel) and specific nuclear energy generation as a function of time and column depth (lower panel). Each darker shading of blue corresponds to a value one order of magnitude higher (see scale on right-hand side of the figure). The tilted black line is the surface of the neutron star and the rise of the line shows the accretion onto the surface of the neutron star (the slope of the line corresponds to the accretion rate).

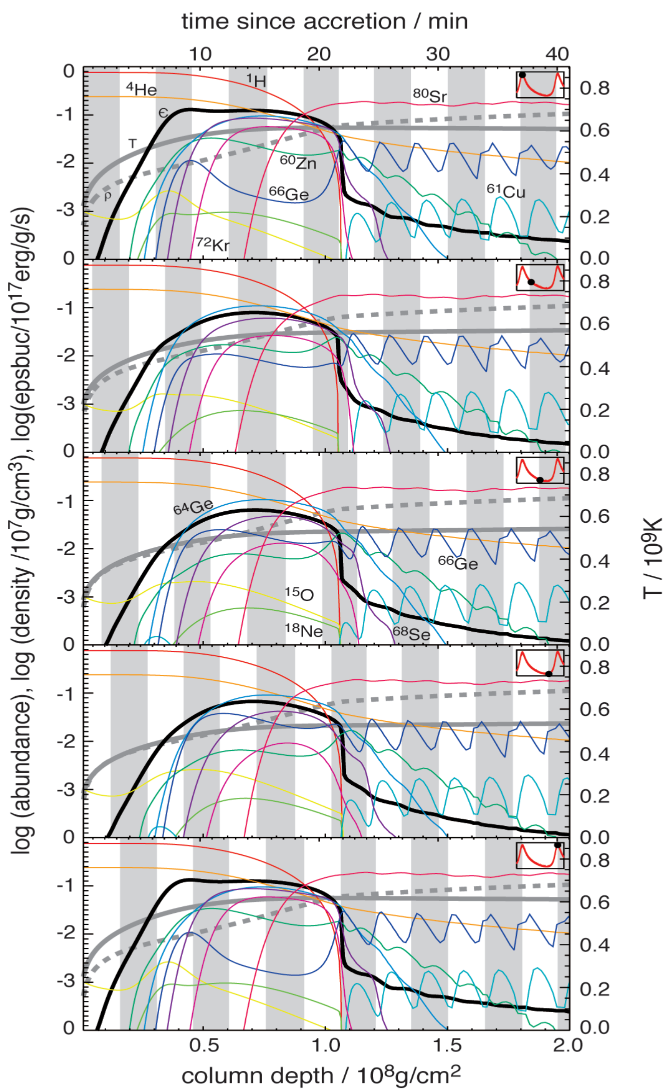

Fig. 3.
Snapshots of structure (temperature: thick gray line; density: thick gray dashed line; specific nuclear energy generation: black line) and composition (select isotopes, colored lines) during one oscillation cycle; each panel is advanced in time by a quarter of the oscillation period relative to the panel above it; the bottom panel is advanced by one full cycle relative to the top panel. The bottom axis for each figure gives column depth, the top axis the corresponding time since accretion.

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