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## Bursting Stars:

Two particular types of explosive events stand out in high-energy astrophysics. One of these, so far detected from within our galaxy, is the sudden release of powerful bursts of X-rays from neutron stars. The second one is known to occur in distant galaxies and defined principally by the $\gamma$-rays that are put out. These X-ray and $\gamma$-ray bursts are among the most interesting dynamical phenomena in astronomy as they teach us about stellar evolution and larg scale structure, as well as fundamental physics. Although they both share an explosive identity, they differ in important ways. X-ray bursts barely damage the underlying star. Thus the stars not only survive the event, but also repeat it. In contrast, $\gamma$-ray bursts completely destroy the underlying object in a spectacular display of cosmic fireworks not seen in other astrophysical contents.

## X-ray Bursts:

X-ray bursts were discovered independently by several groups in 1975. Of the $\sim 200$ X-ray binaries known, about 100 are LMXB's, over half of which are accreting neutron stars. Most of these neutron stars are known to produce X-ray bursts.

The mean quiescent source luminosity of these objects is $L_0 \sim (0.3-2) \times 10^{37}$ erg $s^{-1}$, which is roughly $\frac{1}{10}$ of the Eddington limit. When an X-ray burst goes off, it typically has a rise time $\lesssim 1s$, lasts $3-1000$ s, and recurs on a timescale $\sim (10^3 - 10^6)$ s. The bursts have luminosities $L_b \sim 10^{39}$ erg $s^{-1}$ and total energies $E_b \sim 10^{39} - 10^{41}$ erg. Note

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that $L_b$ is near or above $L_{edd}$. Of the X-ray burst sources, ~ 35 exhibit photospheric expansion, which is consistent with the view that the neutron star's atmosphere is blown away when the luminosity exceeds $L_{edd}$.

The primary evidence for the thermonuclear interpretation of X-ray bursts comes from a comparison between the time-integrated quiescent and burst fluxes: $\frac{L_b}{L_o} \sim 20-300$.

The thermonuclear flash model has been very successful in reproducing the basic features of the X-ray burst phenomenon, which include the short rise time, the recurrence timescales, the luminosities, the energies released, the spectral softening as the burst decays, and the $\frac{L_b}{L_r}$ ratio.

X-ray bursts are caused by the unstable burning of freshly accreted H/He on the surface of the neutron star, which is accumulated over a period of a few hours to form a layer of $\sim 10$m thick. The accreted matter contains very small amounts of heavier elements since the binary systems are very old and belong to population II stars. As the accretion continues, the nuclear fuel is compressed and heated hydrostatically. Therefore both the density and temperature of the accreted layer increases (the highest increase happens at the bottom) until the hydrogen starts burning into helium. This first happens in a thin shell via pp-chain as temperature is initially low. At high temperatures H burns into Helium via the CNO-cycle, and He in turn burns to C via the triple-$\alpha$ reaction.

At high densities electrons become degenerate. As a result, the main contribution to the pressure in the envelope is provided by the degeneracy pressure instead of the thermal pressure. Increasing temperature therefore does not result in a pressure gradient, which would lead to its self-regulation. Instead, the rise in the temperature will increase the rate of nuclear reactions, thus enhancing the burning rate. This further raises the temperature feeding a runaway cycle that results in various Combinations of H and He flashes. The flash will eventually end when the Condition crosses back to non-degenerate, at which point a large pressure gradient arises and pushes the accreting matter back.

The burst spectrum is essentially a black-body. Under the assumption that the emitting surface is spherical, one derives a photospheric radius that is smaller than the neutron star radius. This suggests that only a portion of the neutron star surface burns and radiates at any given time during the event. The neutron star's magnetic field may play an important role here.

It has long been thought that a strong magnetic field stabilizes the nuclear burning by funneling H and He onto the polar caps where heightened temperature causes the nuclear fuel to burn more rapidly and thus avoid the pileup of the matter. Recent discoveries show that the flash still occurs but at the magnetic poles of the neutron star, which then propagates around the star. A very important question arises that how the nuclear burning actually propagates across the stellar surface. This is a subject of considerable interest in computational astrophysics, where these processes are modeled with high resolution grids and state-of-the-art nuclear reaction network and equation of state.

The developing wisdom is that nuclear burning can propagate on a neutron star in three different ways. In a deflagration wave the burning front is unstable (convectively or turbulently) and propagates at a speed $v_{flame} \sim 10^6$ cm $s^{-1}$, spreading over the neutron star in a matter of seconds. If the burning ignites at a density $\gtrsim 10^7$ g $cm^{-3}$, the burning front turns into a shock wave, forming a detonation wave that propagates at a velocity $v_{deton} \sim 10^9$ cm $s^{-1}$, which spreads over the star in a few hundredths of a second. If a very strong magnetic field ($B \gtrsim 10^{11}$ G) is present, the burning front does not turn into a detonation wave and convection and turbulence are suppressed. In this case, the disturbance is mediated via a conduction wave propagating at a speed $v_{cond} \sim 10^3 - 10^4$ cm $s^{-1}$, which takes several hundred seconds to spread across the neutron star's surface.

As an aside, we note that in X-ray bursts the flame propagates within 10 m of the surface, and hence is easily observable. In the case of Type Ia supernovae and classical novae (both associated with white dwarfs), the burning takes place deep inside the star, which makes it impossible to see the process from outside. Also, since a typical neutron star rotates at few hundred revolutions per second, hundreds of snapshots per burst are available to view all points on the neutron star's surface.