Explosions on neutron stars

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Introduction

Neutron stars are very dense objects formed when massive stars come to the end of their lives. Type I X-ray bursts are explosions which occur on the surfaces of some neutron stars. It is believed the explosion begins in a spot in the liquid surface layer, before rapidly spreading across the entire surface, burning as it goes. By modelling this, we can infer neutron star properties such as radius and magnetic field, which are difficult to measure directly but are crucial for understanding the stars' interior physics. My work involves investigating how burning spreads across the surface.

X-ray bursts

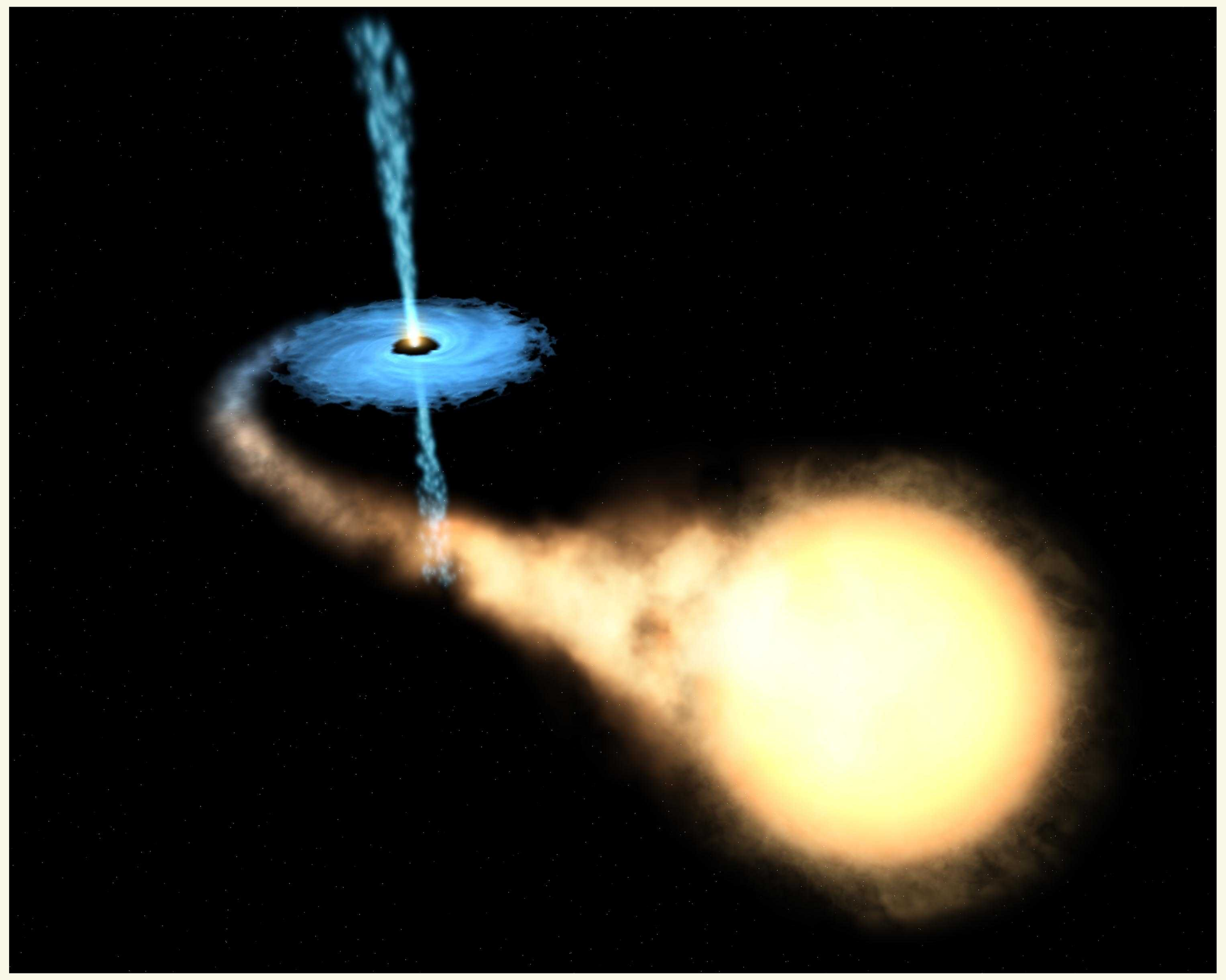

Figure 1: Neutron star in orbit about a low mass star [NASA]

The neutron stars we're interested in are in orbit about low mass stars like our Sun. They pull matter from their companions (see figure 1), and this material makes its way onto the surface, forming a liquid ocean layer primarily consisting of hydrogen and helium. Eventually, the density and temperature in the ocean become high enough that nuclear fusion begins. This is a runaway process, and the nuclear burning very quickly (within a few seconds) spreads across the entire surface of the star. This is observed as a spike in the X-ray radiation of the star, (hence why they're called 'Type I X-ray bursts' - see figure 2).

Strong gravity

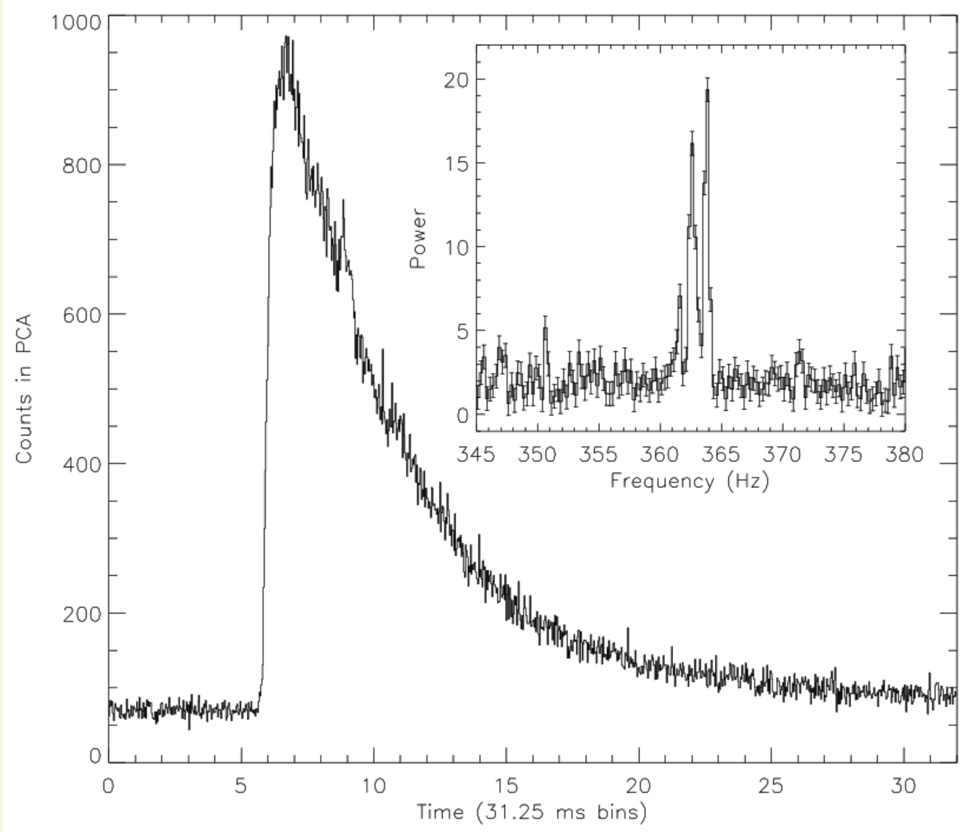

Figure 2: Flux measured during Type I X-ray burst from neutron star 4U 1728-34 [1]

Neutron star oceans are very extreme environments: the fluid is at very high density, pressure and temperature, the stars rotate very quickly and the gravitational field in the ocean is incredibly strong. These effects must be included in our calculations if we are to understand the behaviour of the system. In my work, I describe the strong gravity using Einstein's theory of *general relativity*.

Burning

As part of modelling the bursts, we need to include the physics of the burning itself. As the flame moves across the surface of the star, nuclear fusion reactions change the composition and properties of the fluid, converting the hydrogen and helium into heavier elements such as carbon, heating the fluid and decreasing its density. The burning is highly chaotic or *turbulent* (see figure 3), which makes modelling this process particularly challenging.

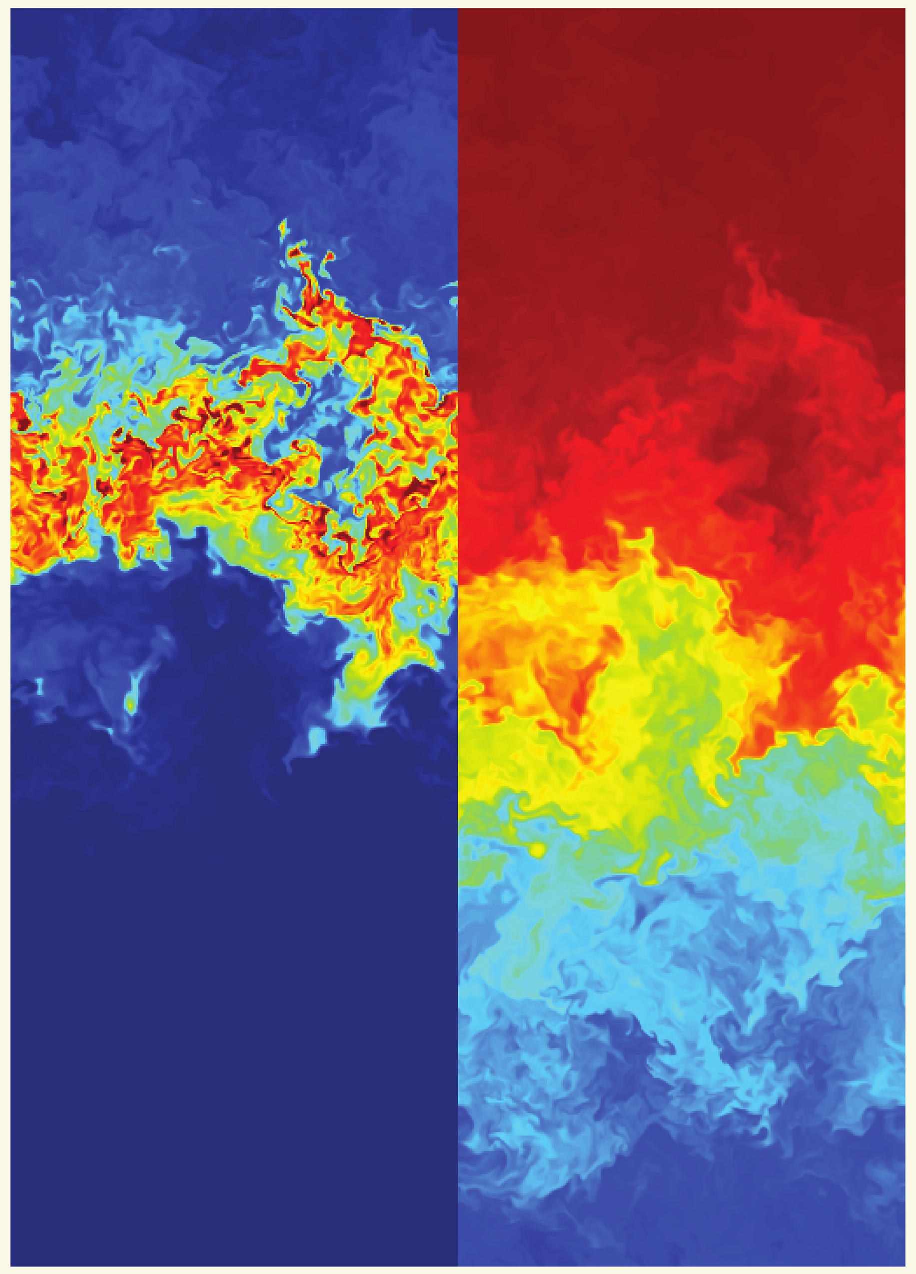

Figure 3: Simulation of turbulent nuclear burning [2]

Modelling

When modelling the system, it's important to account for the fact that the physics works at many very different scales. The burning moves very slowly compared to the sound speed in the ocean, and is much thinner than the ocean depth or the star's radius. We deal with these differences by taking approximations of the full equations in certain limits: I use the *low Mach number* limit, which filters out fast moving sound waves.

Figure 4: Simulation of the *Kelvin-Helmholtz* instability. Two layers of fluid move in opposite directions. The swirling vortices seen in the figure form at their interface.

Summary

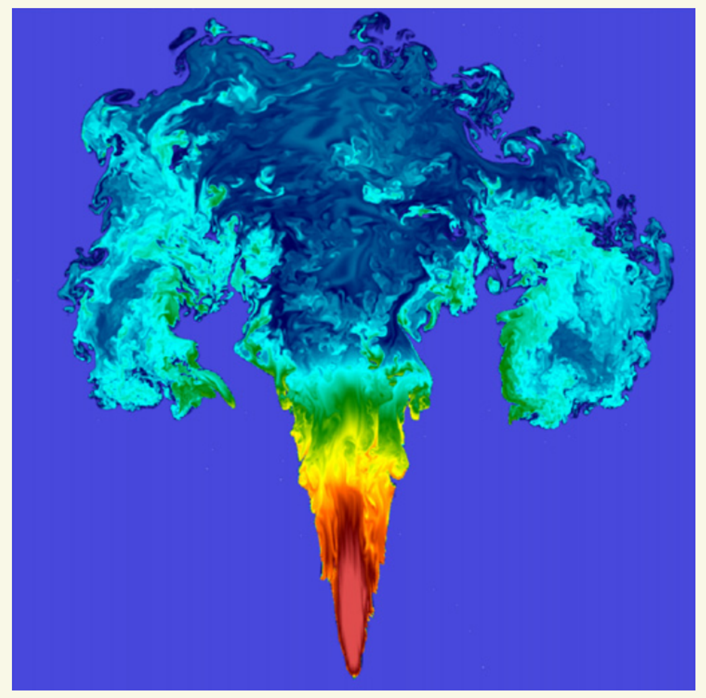

Figure 5: Simulation of a type Ia supernova [3] - plot shows mass fraction of helium.

I will better model X-ray bursts on neutron stars by including strong gravity, fast rotation and oblateness ('non-sphericalness'). This will allow us to better calculate other properties, such as the radius and magnetic field. These are important when investigating the interior structure of neutron stars, which is currently poorly understood and where direct observations are impossible. So far, I have done some small-scale simulations to test the equations (see figure 4); I will next run some larger simulations on the university supercomputer, Iridis.

References

[1] T. Strohmayer, W. Zhang, J. Swank, A. Smale, L. Titarchuk, and C. Day, The Astrophysical Journal **469**, L9 (1996), URL http://iopscience.iop.org/1538-4357/469/1/L9.

[2] A. J. Aspden, J. B. Bell, M. S. Day, S. E. Woosley, and M. Zingale, The Astrophysical Journal **689**, 1173 (2008), ISSN 0004-637X, 0811.2816, URL http://arxiv.org/abs/0811.2816.

[3] C. M. Malone, A. Nonaka, S. E. Woosley, A. S. Almgren, J. B. Bell, S. Dong, and M. Zingale, The Astrophysical Journal **782**, 11 (2014), ISSN 15384357, arXiv:1309.4042v1, URL http://arxiv.org/abs/1309.4042.

Background image: Crab nebula with neutron star at centre [NASA]

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