Peaking into a neutron star: The study of cooling crusts

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INTRODUCTION

When massive stars die in a supernova explosion, they can leave behind the densest directly observable objects in the universe: a **neutron star**. A neutron star has a mass comparable to the Sun, but has a radius of only ~10 km, making it as small as a city. This means that matter in a neutron star is extremely compressed to a level we cannot reproduce using experiments on Earth (see Figure 1). Neutron stars also host the strongest magnetic fields in the universe and have very strong gravitational fields. Therefore, neutron stars are the ultimate **space laboratories** to learn about the behaviour and nature of matter (the building blocks of the universe) in extreme conditions.

How do we learn about the matter inside a neutron star when the neutron star is only as small as a city and many lightyears away? We use neutron stars that are in orbit with a star like our Sun (see Figure 2). When material from the companion star is pulled onto the neutron star surface due to its large gravity this can heat up the outer layer of the neutron star: **the crust**. Using **X-ray telescopes** it is possible to track the neutron star temperature as the crust is cooling down. The cooling rate is set by the structure and composition of the crust. We can use this to test and improve our understanding of the behaviour of matter in the neutron star crust.

Key question: How can we learn about the type of matter inside a neutron star by studying its temperature? How can this method be improved?

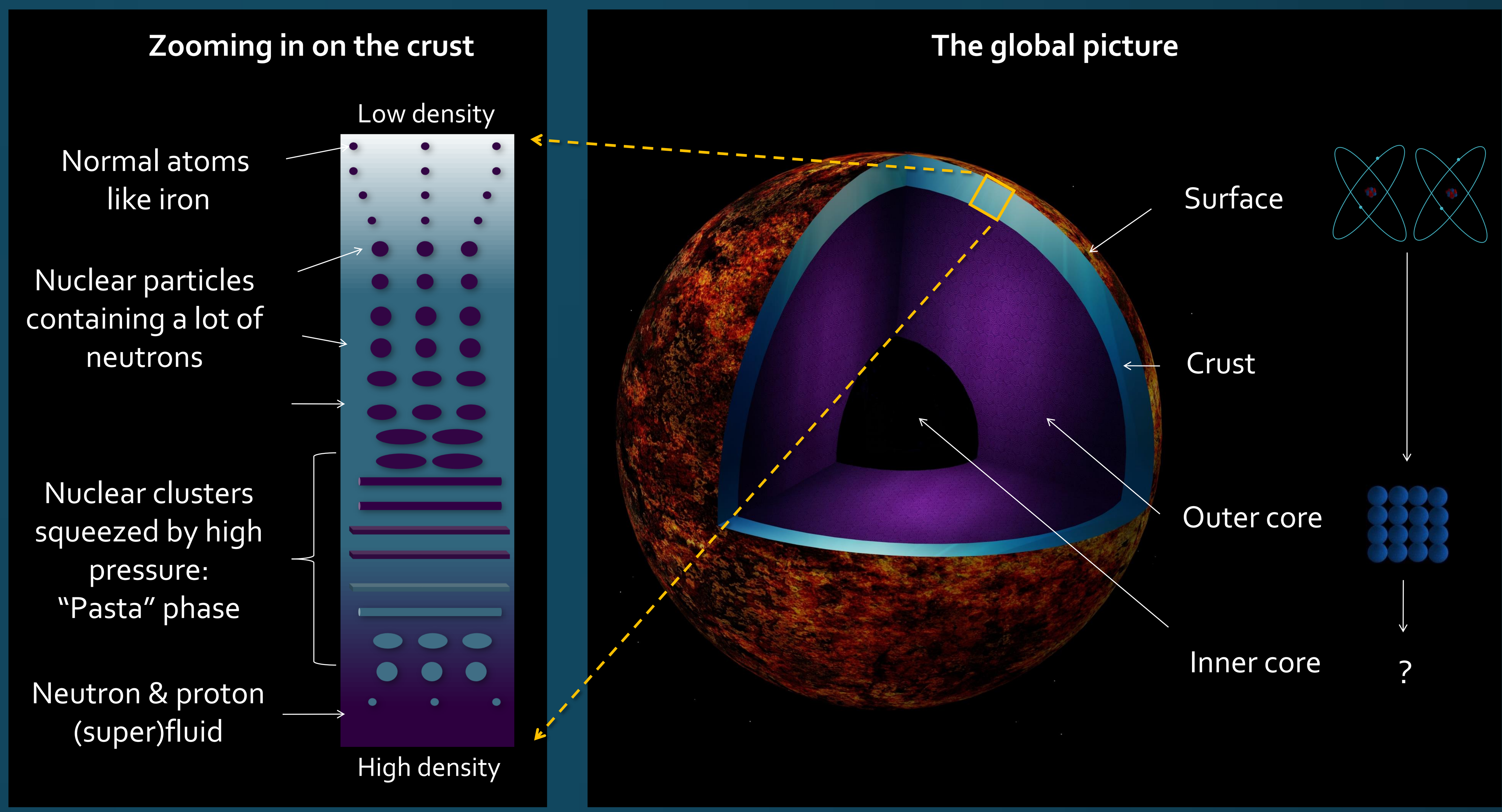


Figure 1. A theoretical view of the neutron star interior. The right panel shows a global view of the neutron star. The left panel shows a cross section of the crust, which is the outer layer of the neutron star. The **crust** is about 1 km in size and connects the surface with the ultra dense neutron star core and contains states of matter that are not stable on Earth. Even though the crust is only a small part of the neutron star, it is crucial to understand if we want to learn more about what type of matter exists in the core and if we want to be able to explain a series of observed astrophysical phenomena. Image credits: Rudy Wijnands (University of Amsterdam).

Summary of method and aim: We use a theoretical model (see Figure 1) of the neutron star crust to calculate the heating and cooling during and after an accretion outburst. We aim to find the properties of the model that can explain the temperatures that have been observed. The details of this method are shown in block 1, 2 and 3 below.

METHOD

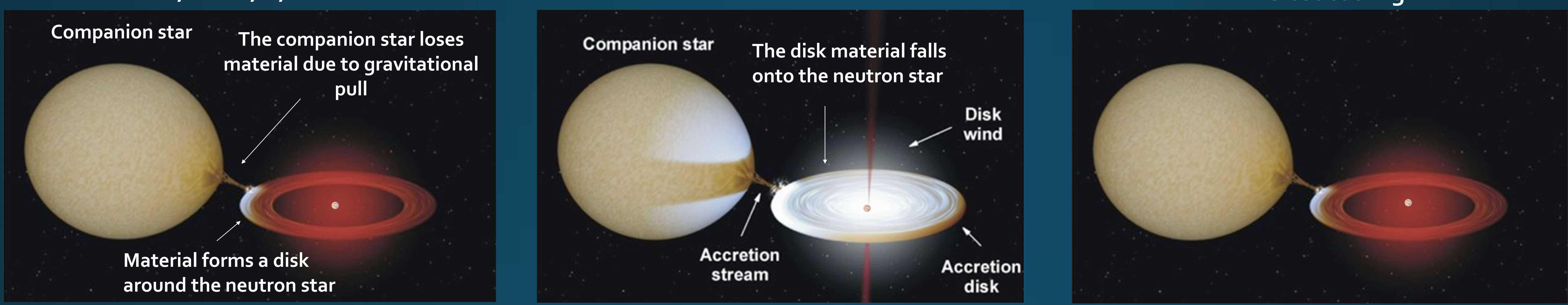
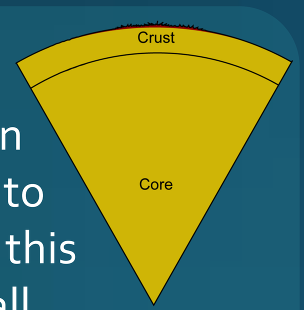


Figure 2. Three stages of the X-ray binary system. Image credits: Rob Hynes (Louisiana State University).

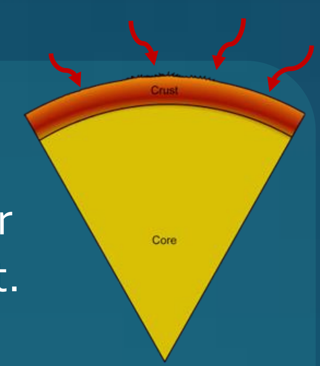
1. Before the outburst



The strong gravitational field of the neutron star causes material of the companion star to be pulled towards the neutron star. We call this process **accretion**. The material does not fall directly onto the neutron star, but forms a disk around it.

If there is no matter falling onto the neutron star, the crust and core have the same temperature.

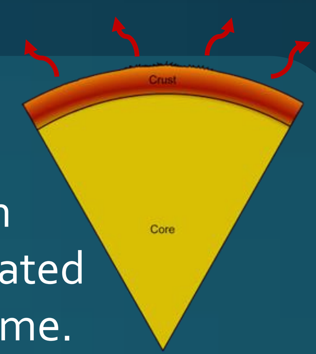
2. Modelling the heating



When material falls onto the neutron star and the system is temporarily very bright.

The infalling material induces a series of nuclear reactions in the crust which can cause the crust to heat up. Based on the brightness of the outburst, we can calculate the amount of heat that is released in the crust.

3. Modelling the cooling



After the accretion outburst, the system returns to its pre-outburst state. The heated neutron star crust will cool down over time. The rate of the cooling depends on its structure and composition.

We compare our model cooling rate to the observed cooling rate.

THIS PROJECT

In this project:

- We have incorporated a routine that uses a smart method to calculate a lot of neutron star models to compare to the data automatically → Saves time!
- We have calculated cooling curves for two neutron stars and found that some layers of the crust could be less ordered than was expected (see Figure 3).
- We will develop a code that has less simplifications so that the effects of magnetic fields can be included. This leads to more accurate results and will also increase the sample size as a lot of neutron stars have very strong magnetic fields.

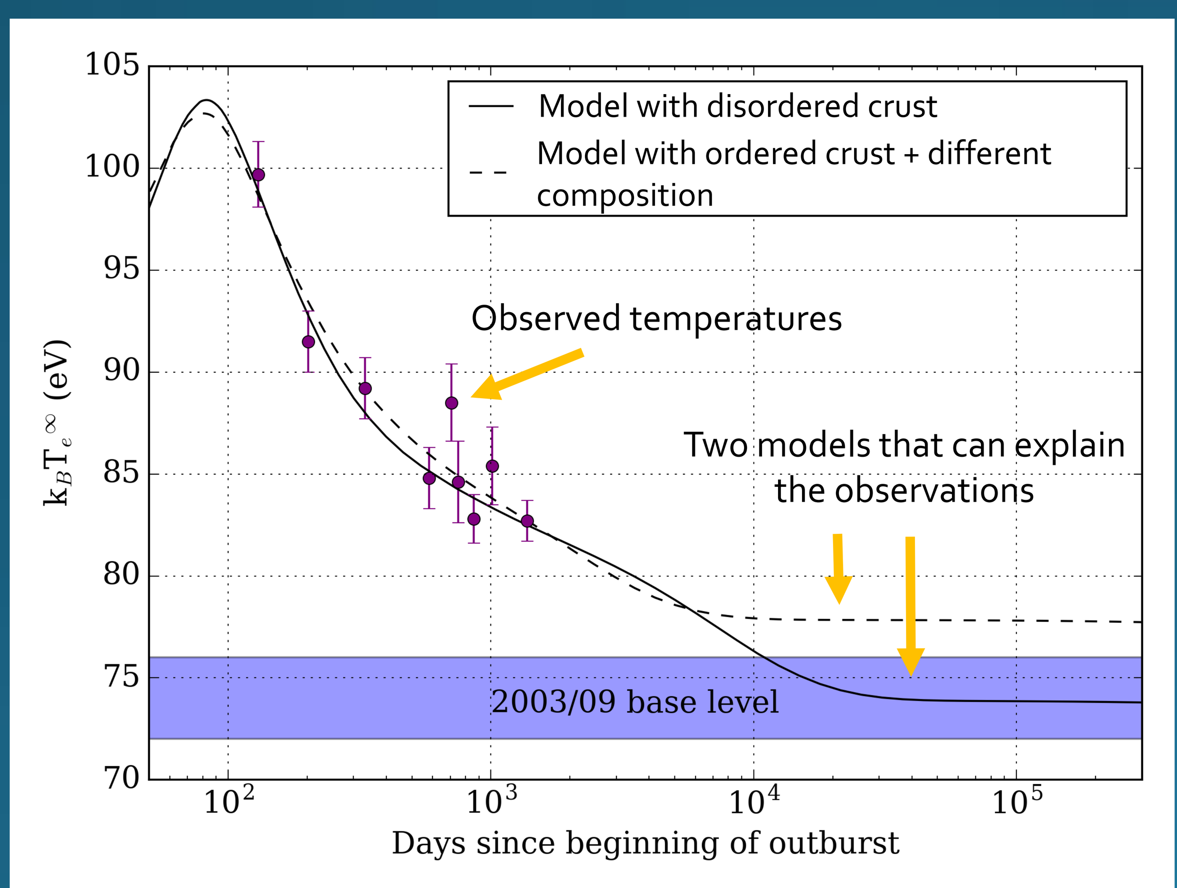


Figure 3. Predictions from calculated cooling curves. [1]

We can use the study of the thermal evolution of neutron stars to infer properties of their interior. By applying a theoretical model to the observed cooling, we learned that the neutron star crust might be less ordered than expected. Currently, we work on extending the model so that it can also be applied to high magnetic field neutron stars.

Scan me for more information, results, videos and further references.

Contact me via:

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This project was partly carried out under the supervision of Rudy Wijnands, Laura Ootes and Dany Page as master project

Credits:

Crust cartoons by N. Degenaar (University of Amsterdam)

[1] Data in Figure 3 from Degenaar et al. (2011)

http://www.astroscu.unam.mx/neutrones/NSCool