The Strongest Material in the Universe

Dr. Matthew Caplan is *a Trottier Chair postdoctoral fellow and Canadian Institute for Theoretical Astrophysics National Fellow working with* **Prof. Andrew Cumming**. *His research primarily concerns the structure and properties of the materials in neutron star crusts.*

Why this is important

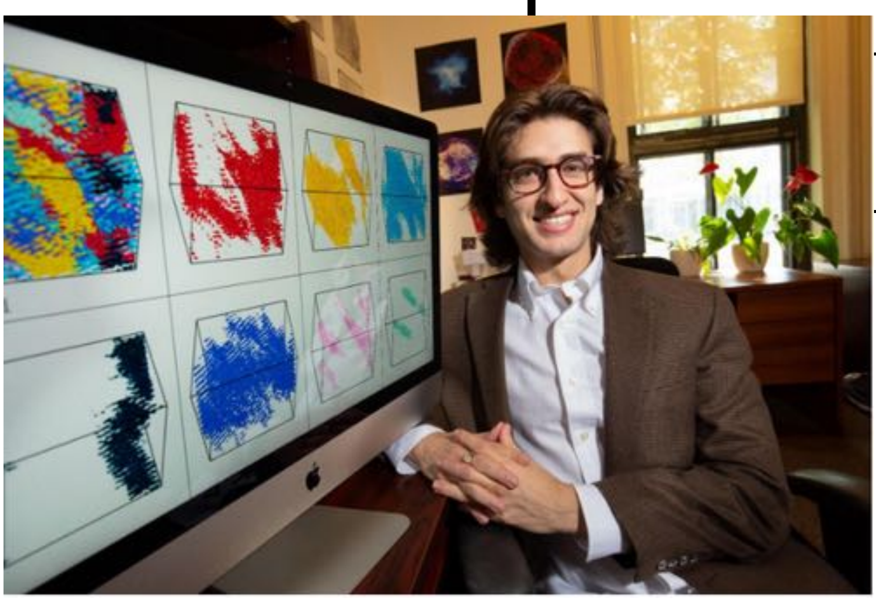
The strength of the neutron star crust is important for a variety of observed phe-nomena. Crust breaking is implicated in pulsar glitches and magnetar outbursts, and limits the size of continuous gravitational wave emission, potentially observable in the near future.

Neutron stars are the densest objects in the universe, and new research by MSI postdoc Matt Caplan now finds that they may contain the strongest material in the universe.

Formed when the core of a massive star implodes in a supernova, a neutron star is like a giant nucleus, with protons and neutrons squeezed so closely together that the mass of the sun fits in a space smaller than the island of Montreal.

But in many ways neutron stars are more like the Earth than a star. Their intense gravity creates enormous pressure which freezes their outer layers solid, giving them a solid crust over a liquid core. Since this crust is the part of the star astronomers can observe, it's essential to understand its properties to probe the interiors of these extreme objects.

On the Earth, the strength of rock can affect the magnitude of earth quakes and the heights of mountains, and neutron stars are no different. The strength of the materials in the neutron star crust may affect similar phe-nomena. Crust breaking on neutron stars may produce electromagnetic radiation and strong materials may support mountains which, if large enough, could radiate gravitational waves.



Caplan, M. E., Schneider, A. S., & Horowitz, C. J. (2018). Elasticity of Nuclear Pasta. Physical Review Letters, 121(13), 132701.

On left: Dr. Caplan in the MSI with his nuclear pasta simulations.

On opposite page: At the top of the figure are conventional nuclei, 'gnocchi', shown at high densities in a neutron star crust where they nearly touch. Under compression, at a slightly greater density, these nuclei fuse to form the range of shapes seen below such as the cylindrical 'spaghetti' and planar 'lasagna', each increasing with density. Toward the bottom, nearest the core, the density grows and the matter is squeezed together so that the pasta phases invert, with tunnels and round voids such as the 'antispaghetti' and 'antignocchi.'

In 2018, Dr. Caplan published a paper in Physical Review Letters which includes the first ever calculations of the strength of the material at the base of the crust. A kilometer below the surface, the pressure is so great that nuclei get squeezed together and protons and neutrons rearrange into cylinders and sheets of nuclear material, named 'nuclear pasta' for its resemblance to spaghetti and lasagna.

Dr. Caplan and his collaborators performed the largest ever simulations of nuclear pasta, containing over three million protons and neutrons, which took nearly 2 million processor hours to run. These simulations stretched and squeezed the pasta to calculate its strength and study how it breaks. Found that nuclear pasta is the strongest material in the universe, which makes it possible for neutron star crusts to have crustal mountains that are tens of centimeters high. While that may not seem like much, the incredible density of the neutron star crust means that these mountains contain far more mass than the Himalayas. If any nearby neutron stars have mountains this large, they could be radiating gravitational waves which LIGO and other gravitational wave observatories may soon detect.

An Exciting Time to Study Neutron Stars

Prof. Andrew Cumming

We are learning more and more about the interiors of these dense stars, thanks to new kinds of observations, particularly those that reveal the response of the star to some kind of transient event. The detection of gravitational waves from merging neutron stars gives a brand new way to study their behaviour as they are ripped apart during the merger. Radio pulsar studies continue to find massive neutron stars that tell us about the maximum pressure nuclear matter can provide. Soon, the Neutron Star Interior Composition Explorer (NICER) experiment on the International Space Station should report accurate measurements of the size of neutron stars. We can now observe cooling of neutron stars for years after heating events which tells us about their heat capacity and whether they contain exotic particles other than neutrons and protons. Ever since their discovery more than 50 years ago, theorists have debated about what is happening inside neutron stars, we are living in an exciting time where these theories are being put to the test.