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Making astrophysical simulations more accurate

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Research work at UiS (Universitetet i Stavanger - The University of Stavanger) and NTNU (Norges teknisk-naturvitenskapelige universitet - The Norwegian University of Science and Technology) may result in better simulations of large astrophysical events such as supernova explosions. This work also raises hopes of finding out more about how atomic nuclei behave in neutron stars.

The work, which was published in December 2015, was carried out by Tomas Brauner at UiS together with Professor Jens Oluf Andersen and William Naylor of NTNU. The physics group at the University of Stavanger collaborates on many research projects with NTNU.

Extreme conditions

Tomas Brauner's field in theoretical physics is matter under extreme conditions. He asks us to consider the sun, the surface temperature of which is a few thousand degrees. This is far from what these researchers call extreme.

"With regard to both temperature and density, what we call extreme is billions higher than that", says Brauner.

Most people know that an atom consists of a nucleus with protons and neutrons and electrons that circle the nucleus. If you imagine an atom the size of a football pitch that is about 100 metres long, then the nucleus would be about the size of a nail head, i.e. about one millimetre. But even though the nucleus of an atom is extremely small, almost the entire atomic mass is found in the nucleus and the rest – the entire football pitch – contains practically no mass.

One of the things that Brauner and his colleagues worked on was looking at atomic nuclei being squeezed together so that the atomic nuclei came near each other. When you squeeze them together, the distance becomes one hundred thousand times smaller than it normally is within the atom. But this is not easy, because the negatively-charged electrons will repel each other. "Extreme pressure is needed to achieve this", Brauner explains.

In neutron stars, it is gravitational pull that is responsible for this pressure. The sun has a radius of about 700,000 km. Take all this mass and squeeze it into a radius of 10 km.

"This is what we mean by extreme density. The gravitational force increases very quickly when things come near each other. This extreme pressure squeezes matter together, and matter is kept together by enormous gravitational forces", says Tomas Brauner.

We are now getting to the core of Brauner's and his colleagues' contribution to astrophysics. Neutron stars and black holes result from supernova explosions. Such an explosion occurs when a star's energy sources are exhausted, and it collapses. Astrophysicists know everything about gravitational pull and how matter behaves in, for example, neutron stars, but they need information about what happens to the nuclei within the atoms, and this is where we come in with results from microscopic physics.

"Among other things, we can estimate and say something about the pressure that counteracts, or tries to resist, the gravitational compression", explains Tomas Brauner.

Four basic forces that are at work in the universe have been found: gravity, electromagnetism, the strong nuclear force and the weak nuclear force, where the latter two have to do with the level at which atomic nuclei interact with each other.

Complex calculations

The strong nuclear force is the one that we will discuss here. This is also called quantum chromodynamics or QCD. Predictions regarding this theory were postulated early in the 1970s by David Politzer, Frank Wilczek and David Gross, and they were awarded the Nobel Prize in Physics in 2004.

"We have been quite certain for over 40 years—and firmly believe—that QCD is the correct theory regarding what happens when atomic nuclei interact, but it is extremely difficult to do calculations based on the theory. Only large-scale computer simulations are capable of this", says Brauner.

And even here it is challenging. The conditions that interest Brauner and his colleagues are very high densities and vast amounts of compressed matter. Right now, such calculations are just too complex. The calculations would take years, and even when you are dead and buried, the computers would still be working on them.

Approximate models

The situation is that you have a theory that is right, but you cannot do simulations based on the theory. A way around this has been to use simpler models. This gives more approximate results, but, in any case, Brauner is able to do calculations with the PC he has in his office. Our job has been to understand the relationship between the precise theory and the rather more approximate model that can be used to do calculations.

The model they have used is the Nambu-Jona-Lasinio or NJL model that was named after the Japanese-American physicist Yoichiro Nambu (the Nobel Prize winner in 2008) and the Italian Giovanni Jona-Lasinio. This model has been around for almost 50 years and has been used to measure the mass of particles such as protons and neutrons, among other things. In the last 20 years, it has also been used in parallel with numeric simulations in nuclear astrophysics research.

It is a very popular model. Consequently, what Tomas Brauner and his colleagues found when they studied the relationship between this theory and model was surprising.

Missing link

Basically, when you create a model based on a theory the symmetry must be right. This is the guiding principle of modern physics. In the microscopic world, this means that particles, for example, have similar properties. When you construct a model of a theory, the details may be approximate, but the symmetry must always be there as the starting point. We now come to the first discovery in the work of Brauner and his colleagues. There was something wrong with the equations used in this model.

"Two terms in the equation were missing. People tend to simplyfy things and this was overlooked", says Brauner.

Accurate simulations

They did not use the QCD theory to find the missing pieces in the use of the NJL model but a similar theory where the results of large simulations had already been produced. The predictions in the NJL model were compared with these results.

He believes that their discovery will be useful for others.

"The NJL model is used to make predictions that astrophysicists need for their work. Now, we have demonstrated that in order to make accurate predictions something must be added to the model. Thus the results and input data we can deliver to astrophysicists help to make astrophysical simulations more accurate", says Brauner.

Quark soup

The work of Brauner and his colleagues also resulted in another major finding, and now we will take a look at quarks. Each proton and each neutron in an atomic nucleus contains three quarks. Under normal circumstances, it is not possible to observe these quarks individually. You cannot isolate them in experiments, and they are not found in isolation in nature.

But what happens to these quark clusters when you heat matter to very high temperatures? The nuclei melt and dissolve to form a type of quark soup. This is referred to as quark–gluon plasma (QGP). In June of last year, physicists managed to produce quark–gluon plasma using the particle collider, the Large Hadron Collider, at the European Organization for Nuclear Research (CERN).

This quark soup consists of quarks that are now free and gluons (which is the particle that binds quarks together to form protons and neutrons, among other things). It is believed that a few microseconds after the Big Bang, also known as the Quark Epoch the universe existed in such a quark–gluon plasma state.

Quarks in neutron stars

"We know that quarks are released when the nuclei melt and become plasma, but what we do not know is the structure of matter with such high densities as those found in neutron stars. Are the quarks released when the nuclei are exposed to extremely high pressure, or do they remain locked within the nuclei ?" Brauner wonders.

He believes that a solution to this puzzle that people have been trying to understand since the 1970s will not just have an enormous influence on astrophysics but also will deepen our understanding of what goes on in atomic nuclei.

Using computer simulations from other theories as input data, the research group has discovered how the NJL model can be used to accurately describe the properties of matter under astrophysical conditions. They show in the research article how the model should be set up to reproduce the result. The results will lead to more accurate descriptions of the core matter in neutron stars, which will be directly relevant to astrophysics. Data from such model calculations is used, for example, as input data in simulations of supernova explosions.

When the research article was presented in *Physical Review D* in December 2015, it was featured as the editor's suggestion. Only 1-2% of contributions to the journal are singled out for such praise.

More information: Jens O. Andersen et al. Confronting effective models for deconfinement in dense quark matter with lattice data, *Physical Review D* (2015). DOI: 10.1103/PhysRevD.92.114504

Provided by University of Stavanger

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