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MEASURING THE UNKNOWN FORCES THAT DRIVE NEUTRON STAR MERGERS

Interview with Professor Eliot Quataert

BY CASSIDY HARDIN, MICHELLE LEE, AND KAELA SEIERSEN

Professor Eliot Quataert.

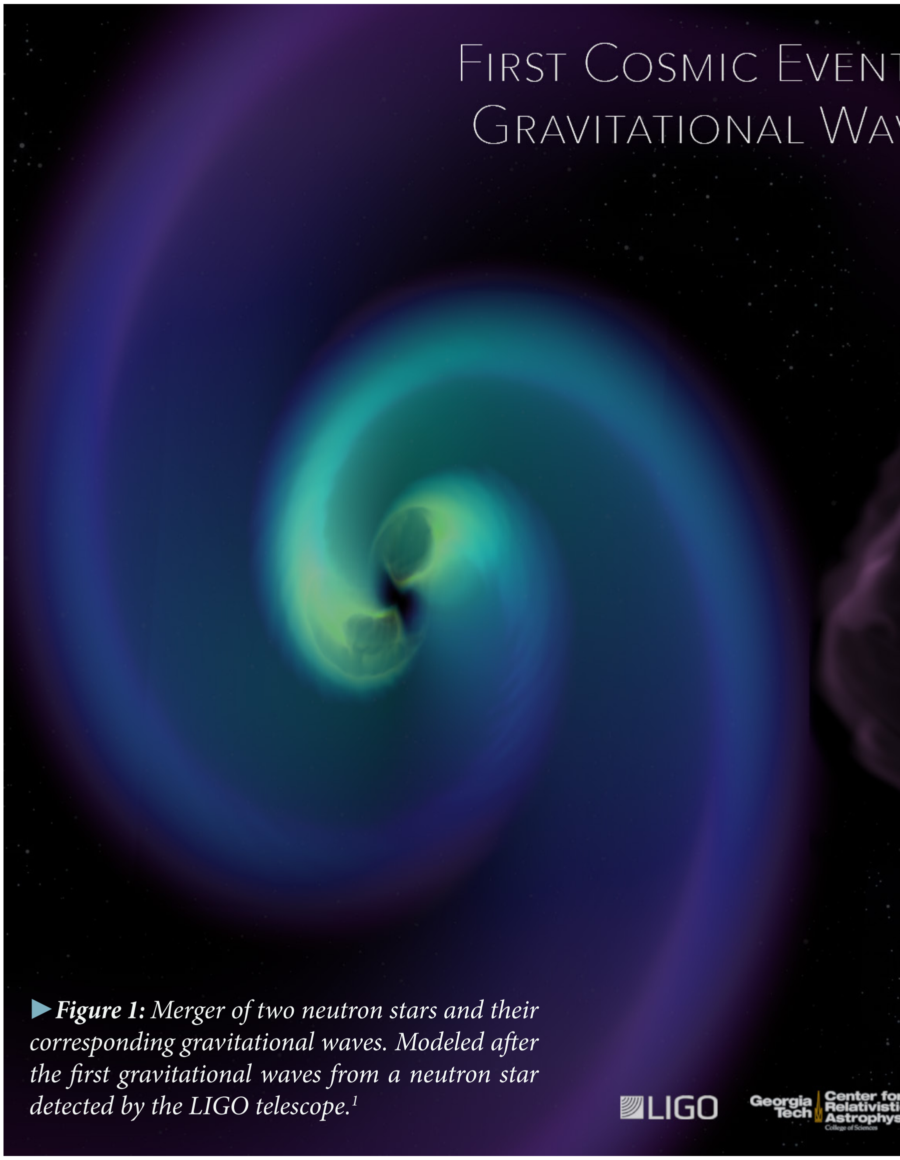

Figure 1: *Merger of two neutron stars and their corresponding gravitational waves. Modeled after the first gravitational waves from a neutron star detected by the LIGO telescope.*[1]

Eliot Quataert *is a Professor of Astronomy and Physics at the University of California, Berkeley. He is also the director of the Theoretical Astrophysics Center, examining cosmology, planetary dynamics, the interstellar medium, and star and planet formation. Professor Quataert's specific interests include black holes, stellar physics, and galaxy formation. In this interview, we discuss the formation of neutron stars, the detection of neutron star mergers, and the general-relativistic magnetohydrodynamic (GRMHD) model that was used to predict the behavior of these mergers. Analysis of these cosmic events is significant because it sheds light on the origins of the heavier elements that make up our universe.*

BSJ: What originally interested you in astrophysics? Why did you start studying black holes and stellar evolution?

EQ: I was interested in physics and math as a high school student, and I was also drawn to more abstract things—I was not much of a tinker. I grew up in the country and was interested in photography, so I did a lot of night sky photography, and I think that was partially what got me interested in astronomy. When I was an undergraduate at MIT, I thought I wanted to study physics, and there wasn't a separate department for astronomy. I was really interested in doing research, and the first project I worked on was in an experimental lab. I hated it and did not think I was very good at it, so I knew I wanted to find a theoretical project next. My first theoretical project was studying sound waves of the sun, which for the most part is very different from what I do now. It was really getting involved with research that allowed me to realize that I love astrophysics. One of the great things about astrophysics relative to particle or string theory is the close connection with observation. This interplay between the abstract, theoretical things I do and the observational side is really fun and exciting, and it also keeps my research grounded in reality. I think this combination is what really convinced me to do astrophysics in graduate school. Right now, I'm working on relating stars with black holes and investigating how stars collapse at the end of their lives. In some cases, if the exploding star forms a black hole, the surrounding material can form a disk around it, which can do all kinds of interesting things. I am trying to study this process.

BSJ: What are neutron stars and how do we observe them?

EQ: Neutron stars are the smallest stars we know of that we can still call normal stars, as opposed to black holes, which are smaller and weirder. Neutron stars consist of materials about the mass of the sun that have been condensed to the size of the Bay Area—roughly 10 kilometers in size. They are extraordinarily dense because you have all this material in a very small region. Under these conditions, the protons and electrons that make up normal matter are forced to combine into neutrons. This is why the matter does not end up as the standard elements we are familiar with such as hydrogen or helium. Rather, these stars are big balls of mostly neutrons, and the conditions in the star resemble those in an atomic nucleus, where the neutrons are packed close together. We observe neutron stars mostly through their light. They emit radio light in a clock-like manner called radio pulsars. We have observed thousands of these in our galaxy. Just recently, we were able to observe neutron stars in gravitational waves as opposed to normal light. When two neutron stars get close and spiral around each other, they alter gravity in time. This information that gravity is changing in time goes out into space in the form of waves, which Einstein had predicted, called gravitational waves. A telescope—the Laser Interferometer Gravitational-Wave Observatory (LIGO)—was able to detect the merger of two neutron stars through the measurement of gravitational waves that were created in the final 10 seconds of the merger.

BSJ: Could you tell us more about how neutron stars merge?

EQ: The Earth orbits around the sun, but it does not fall into the sun. In the case of two neutron stars orbiting close to each other, the gravitational waves take energy out of the system and cause the two neutron stars to move closer to each other. You can think of it loosely as gravitational friction, where friction causes things to slow down. In this case, friction causes the orbit to slowly spiral in. The two neutron stars slowly get closer to each other until they eventually become a single star. Although we are

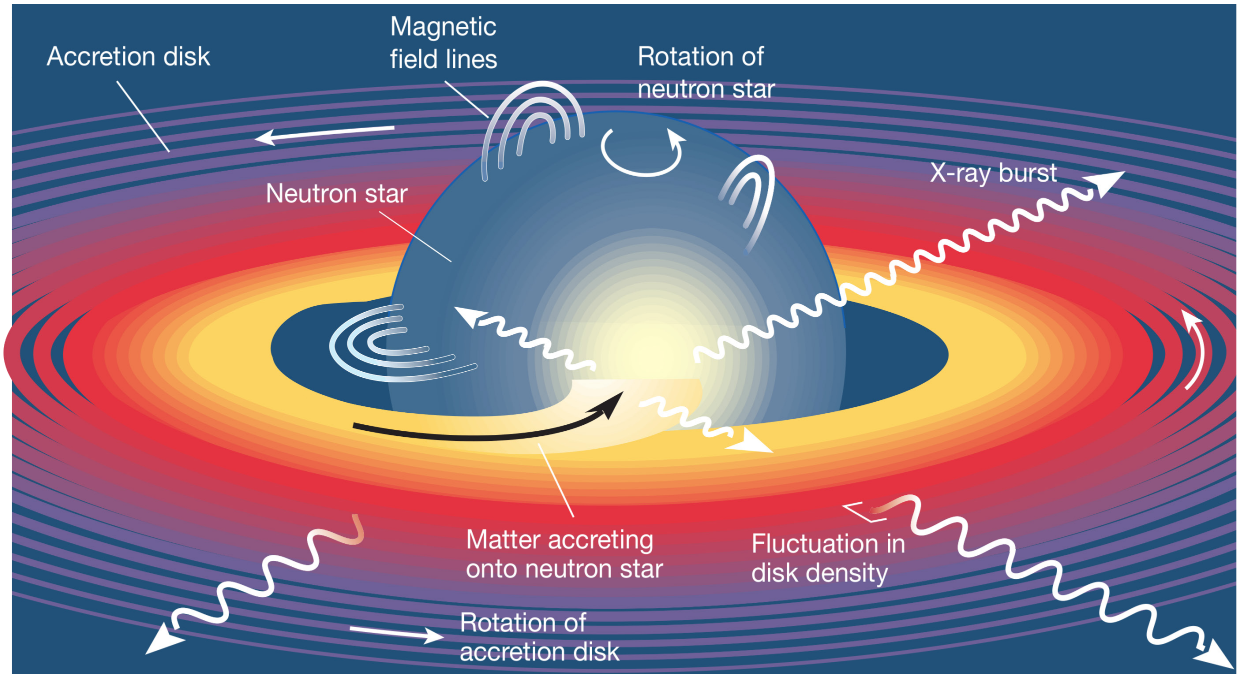

Figure 2: *Annotated diagram of a neutron star and its surroundings.*[3] *When a massive star dies and collapses after a supernova, the core is unable to withstand its massive gravity and all the atoms lose their structure, forming a neutron star. During this formation, the star has a very high spin and matter flies out, creating an accretion disk. This diagram portrays the behaviors of a neutron star and what happens around it.*

not sure yet, this star likely collapses to form a black hole. We've used telescopes on Earth to measure the gravitational waves, and over time we observe these waves getting stronger and stronger until they eventually disappear. The waves disappear when the two neutron stars merge, forming a new object that sits there in space, not producing any gravitational waves.

BSJ: When two neutron stars collide, remnants fly out and create accretion disks surrounding the stars. What is the importance of studying the remnants of these mergers?

EQ: In general, accretion disks are a way of producing light and energy. You have a central object and you have stuff orbiting around it. If the central object is a neutron star or a black hole, the matter that orbits around it is moving really fast. As this matter moves around the central object, it gets really hot and can produce a lot of light and material that is flung out into space. The importance of accretion disks in general is that they produce some of the brightest sources of light we are able to see. In this recent case, we think the collision between two neutron stars produced what is likely a black hole with some sort of disk around it. This disk then flung some material out into space, creating and releasing many heavy elements. Initially, this material was mostly neutrons because they are the main component of neutron stars. As the material was flung out into space, the neutrons and the few protons that were around started to combine with each other to form heavier nuclei. We think this event produces elements like gold, platinum, uranium, and some of the rare, unusual heavy elements in the periodic table that we haven't really found the origin of in nature. This event was sort of a confirmation that those elements could be produced through the collisions of neutron stars.

BSJ: You used a model called the general-relativistic magnetohydrodynamic (GRMHD) simulation to predict the behaviors of the accretion disks and the mergers of neutron stars.[2] Could you briefly describe this model?

EQ: If you're near a neutron star or a black hole, you are moving so close to the speed of light and the gravity is so strong that Newton's theory of gravity and motion doesn't really apply. Einstein's theory of general relativity gives us a more complete model. The magnetohydrodynamic aspect of the model looks into how charged gases subjected to electric and magnetic forces behave. It's a theory for something similar to the atmosphere of the Earth, but in Earth's atmosphere, gas is mostly neutral, so it doesn't interact with electric and magnetic forces. However, if we want to describe a gas where these forces are important, we need a model that can measure that. This particular model tries to study how material would orbit around a black hole in a disk, how the material would get blown away, and how that could be observed.

BSJ: What are the differences between gravitational waves and electromagnetic waves, and how were you able to use their data to create the GRMHD model?

> **“The gravitational waves allowed us to see the collision itself, and the light we observed was from the materials that were flung off from the collision.”**

EQ: All forms of light—radio waves, X-rays, gamma rays—are basically changes in the strength of electric and magnetic fields. These waves travel through space at the speed of light and carry information that we are able to observe at the right wavelength. Gravitational waves are something completely different. Small changes in the strength of gravity travel through space at the speed of light. Thanks to their inherently different properties, if you can see both electromagnetic and gravitational waves, you learn very different things about what’s going on in the object that produced them. Gravitational waves tell you about the mass, and light waves indicate more about the behavior of the material that was flung off. In the case of these colliding neutron stars, the gravitational waves allowed us to see the collision itself, and the light we observed was from the materials that were flung off from the collision. By probing different parts of the problem, we can see a much more complete story of what happened.

BSJ: Following the 2017 neutron star merger, how accurate were your predictions based on the GRMHD model?

EQ: This paper was actually a collection of computer simulations that took longer than expected. We started the simulations before the merger was detected, and we obtained results after the detection. It turns out that the conditions we simulated were a pretty good match of what we observed. A lot of our initial results were in the ballpark of what we needed to explain our observations. We already knew that when two neutron stars would collide, they would collapse, create a black hole, and throw off a certain amount of mass into space. We had a rough sense of what those numbers were from previous theoretical calculations, so even though we did not know anything about the observations when we started doing the work, we knew roughly what the right thing to calculate was. Now that the observations are in hand and we know exactly what we want to explain, we can go back and make more refined calculations.

BSJ: What is the significance of being able to predict and analyze the behaviors of these cosmic events such as neutron star mergers?

EQ: The truth is these are hard problems, and a lot of the predictions I make do not turn out to be quite so right. You make approximations when you try to figure something out, so what was nice about this case is that most of the predictions were at least roughly right. I think this is of broad scientific interest because it is the first time in scientific history, at least on Earth, that we have seen the same object produce both gravitational waves and light. And that, as I have alluded to earlier, gives us very different information. Now we can learn a lot more about

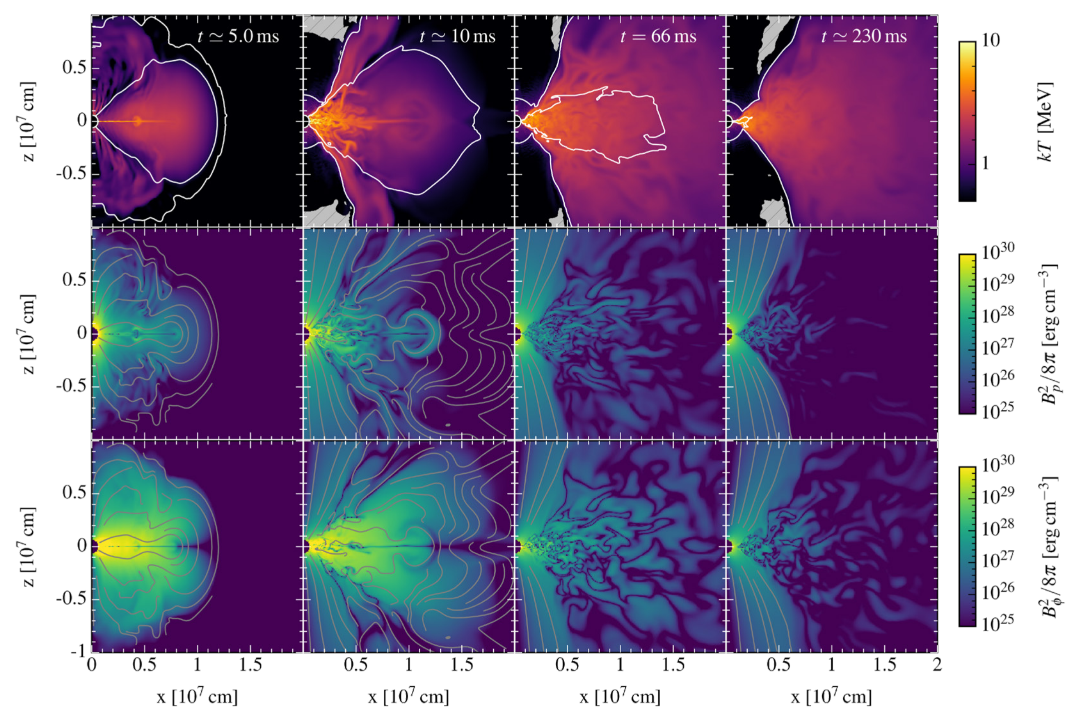

Figure 3: Evolution of the GRMHD model.[2] From top to bottom, each row represents temperature, poloidal magnetic pressure, and toroidal magnetic pressure at four different time points. Magnetic field lines are shown in gray.

what actually happened in the event by combining two different views of the same phenomenon. In addition, we know that there is gold, uranium, and platinum on Earth, but we did not know where in nature these elements actually came from. This event provided evidence that these elements are produced in colliding neutron stars. So, this solves a 60- or 70-year-old problem of identifying where in nature elements that exist on Earth are produced. Understanding the nature of matter, atoms, and protons and neutrons in the nucleus has been an essential problem in physics over the past few centuries. In astrophysics, it has been figuring out where hydrogen, carbon, and iron come from. This particular event helped complete our understanding of the story of where the basic building blocks of everything here on Earth comes from.

BSJ: What advice or activities would you recommend to anyone looking to enter into astrophysics?

EQ: I think there are two important things. One is taking basic physics classes to get a grounding in physics. Another is learning to be comfortable doing calculations with computers, in Python or something like that, because more and more of what we do is computer-based calculations. Even if you can figure something out like algebra and geometry with a pencil and paper, more and more often you have to build computer models of what you are trying to understand. Another thing I encourage students who might be interested in science to do is try their hand at undergraduate research. Research is very different from doing classwork. It is a lot more frustrating, usually, because you don't know the answer. The problem that you are trying to solve usually takes a much longer time. If a homework problem takes five hours, that is usually a long homework problem. In research, there were problems that I worked on that took more than a year to figure out. And frankly, dealing with that frustration is something that people either really like and it becomes motivating, or people get irritated and it is demoralizing. I think that figuring out how you approach that kind of work is very useful, even if you end up working in industry. If you work at a startup, there is a similar, long-term horizon to the kinds of problems that people work on.

> ***"The 2017 neutron star merger is the first time in scientific history that we have seen the same object produce both gravitational waves and light."***

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IMAGE REFERENCES

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