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NEW KNOWLEDGE FROM GRAVITATIONAL-WAVE OBSERVATIONS

Gravitational waves are not a rare phenomenon that happens only once in a while in our universe. Rather, such waves pass through the Earth on a daily basis, generated by cosmic events of various types. Studying their origins can teach us a great deal about the universe at large

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The history of gravitational-wave astronomy begins with Albert Einstein back in 1916, when his theory of general relativity predicted the disruption of space-time in the form of wave-like ripples. For gravitational waves to be produced, there needs to be a shift in the mass symmetry of a body or a system. If we run in circles and then switch to smaller circles, we are disrupting the space-time. If a satellite slightly changes its orbit around Earth this also disrupts the space-time.

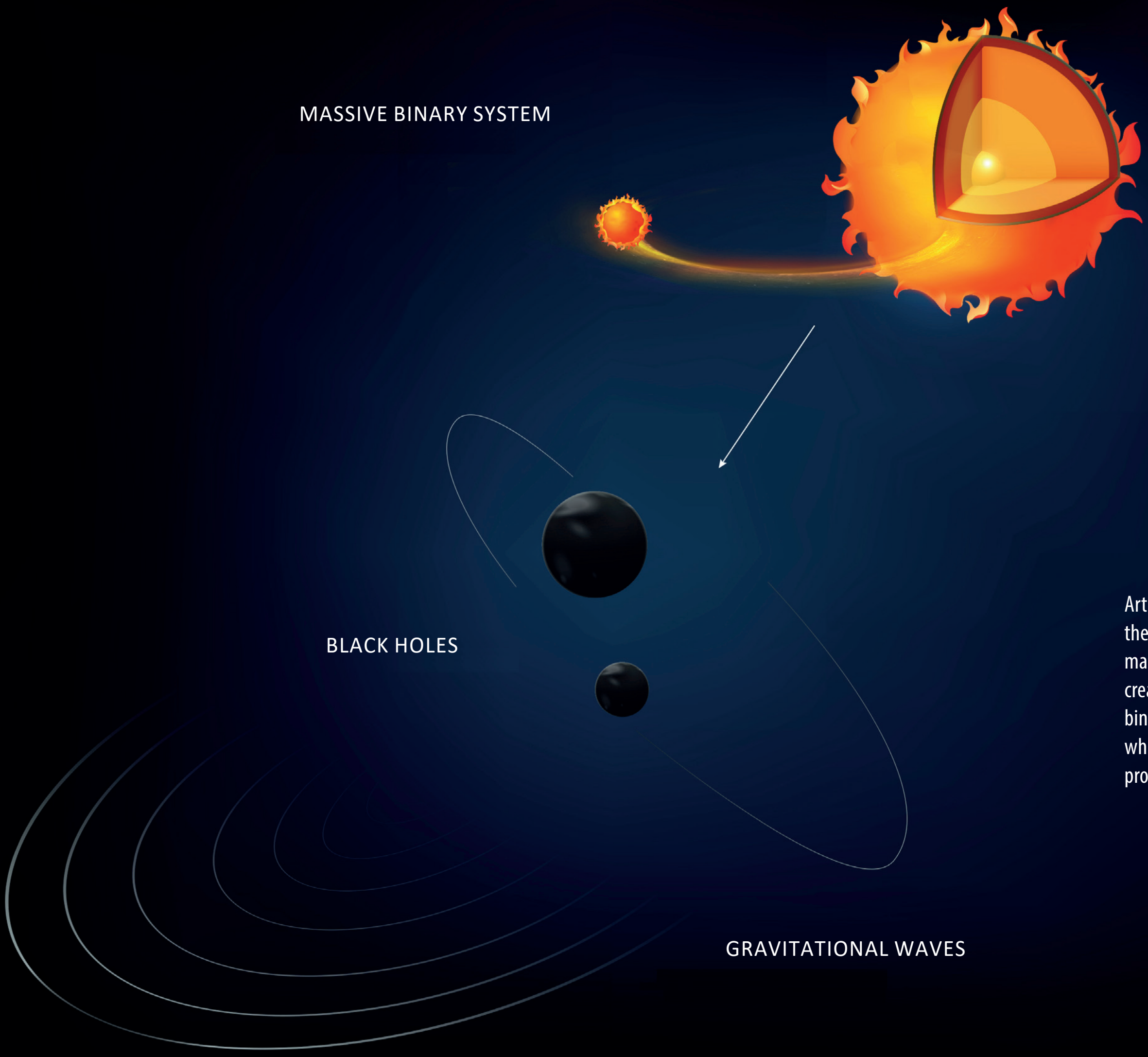
The gravitational waves emitted from these events are nevertheless too weak to be ever detectable in any foreseeable future. There are currently four gravitational-wave telescopes in the world: LIGO Hanford and LIGO Livingston in the United States, VIRGO in Italy, and KAGRA in Japan. In order for gravitational waves to be energetic enough to be detected by these instruments, however, they generally have to be emitted when two very massive objects orbiting around a center of mass rapidly change their orbits. This was the case, for instance, for the world's very first direct observation of gravitational waves, made on 14 September 2015 and announced by the LIGO and Virgo collaborations on 11 February 2016. In general, the current instruments can detect only the waves from black holes and neutron stars that enter an orbit so small as to merge into a single object.

Gravitational-wave origins

Both neutron stars and black holes are the outcomes of dying stars gravitationally collapsing on their cores. Although neutron stars are predicted to be way more abundant than black holes in the observable universe, the vast majority of the gravitational-wave sources detected to date have been black holes, since they are more massive and therefore their merger signal is stronger.

Given that gravitational-wave astronomy is such a nascent field, there are still a number of major uncertainties pertaining our observations and theory. Black hole binary mergers are predicted to come from three major evolutionary channels:

1. **Isolated binary evolution**, when two stars orbiting around each other evolve without the influence of any external body;



Artist's impressiono of how the interaction between two massive stars can lead to the creation of black hole binaries,
whose degenerate orbits produce gravitational waves

GRAPHIC BY KASIA DREWNIANY

2. **Dynamical evolution**, where external bodies are directly involved into the formation and evolution of black hole binaries;
3. **Primordial black holes**, which are a hypothetical class of black holes that are formed not from the collapse of a massive star, but instead from localized energy peaks soon after the Big Bang.

For each evolutionary channel, in turn, there are several sub-channels that can contribute to the formation of binary black holes and to their subsequent merger. Considering our current knowledge of the universe, the most promising evolutionary channel from which most of the observed black hole mergers are supposed to be from is isolated binary evolution.

Binary star systems

In this channel, we usually study two massive stars (more than 5 times the mass of the Sun) which over their lifetimes pass through different evolutionary stages until they collapse into either neutron stars or black holes. One of the most interesting phenomena that may happen in a binary system usually occurs when a star is rapidly expanding. In this phase its outer layers can become so loosely bound to the stellar core as to be pulled out of its gravitational influence by the gravitational force of its stellar companion. This is called a **Roche lobe overflow event** and, as shown in the image below, involves a star "stealing away" part of its stellar companion's mass until either the binary is destroyed or the accretor star is unable to pull anything else away from the donor star. Since this process is not 100% efficient, some of the donated mass does not actually get absorbed by the other star but instead becomes dispersed in the surroundings. For mechanical reasons, this mass loss causes a loss of angular momentum that, in addition to the gravitational imbalance due to the alteration of the mass distribution in the binary, usually brings to shrink the distance between the two stars.

The closer the two black holes or neutron stars are, the faster they will orbit around each other and therefore the stronger the gravitational-wave signal that we will detect. Therefore, a binary passing through a Roche lobe overflow event will be more likely to be detected in the future by our gravitational-wave observatories.

Simulated collapses

With the help of state-of-the-art theoretical and computational models, we have developed (and are continually working to improve) evolutionary codes that are capable of simulating the evolution of massive stars in binary systems from their birth to their final collapse. Some of these codes are capable of simulating the whole 3D (magneto-)hydrodynamics of stars, but take months or more for a single binary system to be simulated. Others are 1D and take "merely" days without losing much in terms of accuracy, while others, if calibrated correctly and with appropriate simplifications, can simulate millions of stars in just a single day. A considerable part of the physics implemented in these codes is not what we call first-principle physics. This means that it does not come from a pure mathematical derivation of natural laws, but rather from taking a descriptive approach to empirical observations. $E = mc^2$ is first-principle physics. The fact that, when we see a thermometer at 0 degrees Celsius, we expect water to freeze comes from a descriptive theory, since we have observed this event in the past and we are expecting the same result. Setting aside the debate on whether pure first-principle physics truly exists, the advantage of using descriptive theories is that we do not have to wait for the mathematical formalism to give us "perfect" physical equations that might also have worked just fine in a more approximated version. The downside is that we need plenty of observations to build a theory of this sort in the first place.

The generic theoretical picture of the physics of how massive stars evolve and behave during Roche lobe overflow events is generally known, but it lacks precision. In every theoretical estimate and simulation of the life of a star, even a small variation in a few physical constants can drastically alter its expansion, chemical composition, stratification, and how it will eventually die.

Massive stars are quite rare in the universe as compared to smaller stars, and considering that they also burn (and therefore die) faster than their smaller siblings, the amount of empirical data that we have at our disposal to understand the high-energy physics happening in their interiors is not overwhelming. On top of that, there are certain physical processes happening inside massive stars that we cannot simply test in our laboratories on Earth. The nuclear reactions happening inside our Sun (which generate all its energy) are testable in our laboratories. The nuclear reactions happening during the latest stages of the life of massive stars, on the other hand, require temperatures of billions to tens of billions degrees Kelvin, which is thousands of times hotter than the highest temperatures that we can reach in our laboratories for nuclear research. This has caused a great deal of problems in theoretical stellar astrophysics: if our models are only constrained by a low number of observations and few experimental results from our laboratories, the resulting physics is fraught with considerable margins of uncertainty.

New source of information

So how can we study the birth and evolution of neutron stars and black holes if we are not even sure of how their progenitor stars evolve in fine detail?

This is where gravitational wave astronomy is revolutionizing the sector. Most (or all) black holes are essentially collapsed stellar cores, and the vast majority are not visible with normal telescopes. Gravitational wave telescopes are now showing us a whole universe of undiscovered black hole binaries merging with each other. As a result, we can better understand how stars evolve, since the properties of stellar cores are directly related to the physics of stars. This physics differs from that involved in the evolution of smaller stars (like our Sun) because massive stars produce way more energy, which drastically affects the behavior of the over-heated stellar plasma and the light produced in its interiors.

We are learning more not only about stellar evolution, but also about the physics behind highly energetic phenomena like supernovae. Although the jury is still out on whether black hole progenitors explode in supernovae or simply implode due to gravitational collapse, we do know that gravitational waves are helping us answering this question. If a star explodes, some of the outer envelopes will be ejected and therefore the resulting black hole will be less massive than its stellar progenitor, whereas if instead there is a full implosion the black hole will inevitably be more massive, as no mass will be lost.

Kilonova events

Neutron stars, on the other hand, are believed – within safe margins of confidence – to be the product of supernova explosions. A distinctive peculiarity of two neutron stars (or perhaps a neutron star and a black hole) merging with each other, as compared to the merger of two black holes, is that just before their fusion they undergo a phase of instability that leads to a runaway nuclear and thermodynamic reaction known as a kilonova event. Such events are associated with a strong, but short emission of gravitational waves, gamma rays, and neutrinos. Kilonovae are responsible for the presence of most of the heaviest elements in the universe, such as gold and platinum. The only neutron star merger event ever registered to date is GW170817, which alone generated ~16,000 times the mass of Earth in heavy elements, in addition to the black hole that formed after the fusion. Observations of neutron star mergers using gravitational wave, neutrino, and canonical telescopes are therefore not only helping us to understand the physics behind massive stellar binaries, but also to better comprehend how the universe and its chemical composition evolved. This, among the other things, gives us further insights into how planets form and how biological life arose. ■

Further reading:

What are gravitational waves? https://www.ligo.caltech.edu/page/what-are-gw

The Evolution of Massive Stars and Type II Supernovae. https://www.e-education.psu.edu/astro801/content/l6_p5.html

Merging neutron stars: The unfolding story of a kilonova told in X-rays. https://www.psu.edu/news/eberly-college-science/story/merging-neutron-stars-unfolding-story-kilonova-told-x-rays/