Gravitational Waves and the Heaviest Elements

Multi-Messenger Signals from Compact Objects

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In Short

- In August 2017 the long-awaited era of "Multi-Messenger Astrophysics" has spectacularly begun: a neutron star merger gravitational wave signal flooded the LIGO detectors for several tens of seconds and over the following weeks the aftermath of the event was observed electromagnetically from gamma-rays over optical to radio wave lengths.
- This observation constrained the propagation speed of gravitational waves, allowed for a new way to determine the Hubble constant, it showed that neutron star mergers produce the heaviest elements and connected such mergers firmly to cosmic explosions called gamma-ray bursts. For all these reasons it was chosen by Science Magazin as "Breakthrough of the year 2017".
- Our project explores complementary channels that provide information on major gravitational wave sources. It includes LIGO/VIRGO sources like merging binaries of neutron stars and black holes, but also tidal disruption events where a star is ripped apart by the tidal forces of a massive black hole.

Introduction

Stars with more than eight solar masses end their lives in cataclysmic fireworks called supernovae. The luminosities of these explosions rival those of whole galaxies. Supernovae eject most of their mass into space where the ejecta form the basis for the next generation of stars. The core of the stars, however, become enormously compressed during the explosion and –if the star was not too massive– the explosion produces a neutron star, or otherwise a black hole of a few solar masses will form. Neutron stars can be thought of as gigantic atomic nuclei: with a mass of about 1.4 solar masses and radii of only 12 km their central densities substantially exceed the density in atomic nuclei ($\rho_{\rm nuc} = 2.7 \times 10^{14}$ g/cm^3).

In some cases two such exotic stars orbit as a binary system around their common centre of mass. Due to their enormous compactness, such stars can revolve around each other at very small separations and in such systems strong-field gravity effects become important, making them

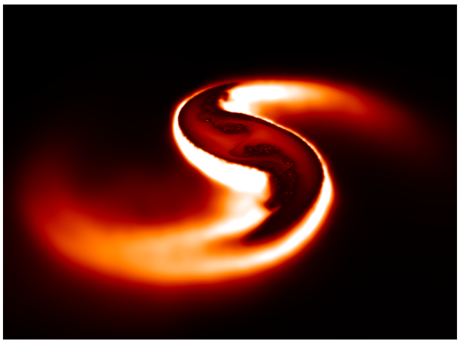

Figure 1: *HLRN simulation of the merger of two neutron stars. Shown is a volume rendering of the density. To allow a view inside, only the lower part of the matter distribution is visualized.*

excellent laboratories to test gravitational theories such as Einstein's theory of General Relativity. In fact, the first –though indirect– evidence for the existence of gravitational waves came from such a neutron star binary system and it earned its discoverers, Russel Hulse and Joseph Taylor, the Nobel Prize for Physics in 1993. One implication of the emission of gravitational waves is that the binary orbit shrinks further until the stars finally merge. This releases gigantic amounts of gravitational energy, more than the Sun could radiate away during the whole lifetime of the Universe. On August 17, 2017 such a neutron star merger has for the first time been detected: the American LIGO detectors recorded the "chirping" (i.e. increasing in frequency and amplitude) gravitational wave signal for about one minute and 1.7 seconds later a short gamma-ray burst was detected. During the following weeks fireworks all across the electromagnetic spectrum were observed. This watershed event marks the beginning of the era of multi-messenger astrophysics where events are observed via several different messengers (e.g. photons and gravitons) that convey complementary information. Already the first such event revealed that a) mergers of neutron stars emit gravitational waves in agreement with Einstein's General Relativity, b) they cause bright cosmic explosions called gamma-ray bursts, c) they forge the heaviest elements in the Universe (such as gold or platinum). Moreover, the delay between the gravitational wave peak and the gamma-ray burst has been used to constrain the speed at which gravitational waves travel: it is equal to the speed of light to within one part in 10^{15}! For these reasons this detection was elected by the Science Magazine as the "Breakthrough of the year 2017".

While this event was a major breakthrough for the physics of 21st century and has brought major leaps forward on many fronts, it left many questions unanswered or triggered new ones, respectively. There is much we hope to learn from the observations of the expanding worldwide network of gravitational wave detectors combined with astronomical telescopes. To interpret such observations and to connect them to the physics of the emitting sources, however, one needs simulations such as those performed within this project. An example of a neutron star merger simulation that has been performed on HLRN resources is shown in Fig. 1.

The power of Multi-Messenger Astrophysics

By receiving information from different messengers, say gravitational waves and light, one may discover entirely new sides of an astrophysical event. For example, in the first multi-messenger detection of a merging neutron star binary the gravitational waves conveyed the physics of the merging binary (e.g. its mass and tidal deformability) while the electromagnetic radiation allowed to place the merger in an astrophysical context: it revealed the location in the sky and allowed to identify the "host galaxy" (including its cosmological redshift) in which the merger took place. Taking the two sides of the story together provides a host of information, both on the past of the observed binary system, its stellar evolution path, and on the involved physics such as nuclear matter properties or the formation of heavy elements.

Tidal disruptions of stars by black holes

But multi-messenger astrophysics is of course not only restricted to binary neutron stars, also many other systems can provide complementary information in different channels. An interesting such event with multi-messenger signatures is the flyby of stars close to a massive black. If the black hole is very massive the star can actually be swallowed by the event horizon without being disrupted. How massive the black hole has to be for this to happen, depends on its own spin and on the type of star that is approaching. For black holes lighter than this critical value, however, stars are torn apart by the tidal forces of the black hole once they pass closer than a critical distance which is called the "tidal radius". The deformation of a white dwarf star that passes just outside the tidal radius of an "intermediate mass black hole" with 1000 times the mass of our Sun is shown in Fig. 2 \HLRNref{rosswog09}. In extreme cases where a white dwarf passes very deeply inside the tidal radius, the tidal forces of the black hole can crush the star so strongly that a thermonuclear explosion is triggered. Such a case is shown in Fig. 3 (from \HLRNref{rosswog09}).

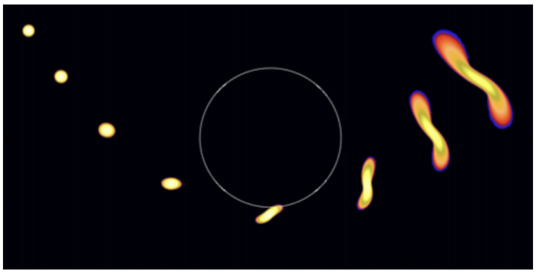

Figure 2: *A White Dwarf stars being torn apart by the tidal forces of a black hole. The circle indicates the so-called "tidal radius" inside of which the star is ripped to pieces. In this case the star was lucky and just passed outside this radius.*

Figure 3: *A white dwarf that entered very deeply into the tidal radius of an intermediate mass black hole. The white dwarf has been disrupted and thereby underwent substantial burning. Approximately half of the white dwarf is bound to the black, falling towards it and thereby building up an accretion disk.*

Outlook

The first multi-messenger observation of a binary neutron star in both gravitational and electromagnetic waves crowned decades-long efforts both on the experimental and theoretical side. The existing gravitational wave network is currently being upgraded and extended and new detectors, such as the space-based LISA mission, are being built. And the science world is eagerly awaiting the next discoveries they will bring. The understanding of future multi-messenger observations depends crucially on simulations such as those of this project.

More Information

[1] S. Rosswog et al., The Astrophysical Journal, Volume 695, Issue 1, pp. 404-419 (2009) doi: 10.1088/0004-637X/695/1/404