The origin of the heavy elements

Electromagnetic transients and heavy elements from compact object mergers and core-collapse supernovae

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In Short

- The astrophysical origin of about half of the elements heavier than iron remains an open question.
- Current observations of colliding neutron stars and black holes through gravitational waves and electromagnetic radiation reveal clues about how such elements are produced. Yet these events may not be the only sources of heavy elements in the universe.
- This project features a suite of pioneering simulations of a wide array of astrophysical candidate systems to explore whether/how these systems can significantly contribute to the cosmic synthesis of heavy elements, including double neutron-star and neutron-star-–black-hole collisions, the collapse of very massive rotating stars, and rapidly rotating proto-neutron stars formed in core-collapse supernovae.

The first detection of a merger of two neutron stars in a binary system by the gravitational-wave observatories LIGO and Virgo in 2017 (called GW170817) inaugurated the field of multimessenger astronomy with gravitational waves, which combines gravitational signals, light, and particles to probe astrophysical objects and events in greater detail than ever before. Via observed quasi-thermal electromagnetic emission from the radioactive decay of heavy elements synthesized in the merger debris—called a 'kilonova'—, such multimessenger sources provide clues about the synthesis of about half of the elements heavier than iron. The astrophysical origin of these so-called r-process elements has remained a key open question in astrophysics ever since the foundations of the nuclear physics processes required to synthesize them had been realized the 1950s.

Numerical simulations are a critical tool to understand the complex physical processes involved in the synthesis of heavy elements in multi-messenger systems and to predict their observable electromagnetic emission, including the kilonova. There is both empirical and theoretical evidence that multi-messenger sources other than double neutron-star mergers may also significantly contribute to the overall production of r-process elements in the universe.

This project explores by means of detailed sumpercomputer simulations the conditions for r-process nucleosynthesis over a wide array of astrophysical candidate sources, including the collisions of two neutron stars in a binary system, collisions of a neutron star and a black hole in a binary system, the collapse of very massive, rapidly rotating stars (collapsars), and proto-neutron stars formed as a result of the core-collapse of massive stars.

Double neutron-star collisions. Figure 1 presents a schematic overview of different channels for ejection of r-process elements in neutron-star mergers, based in part on previous simulation results by the project team. While previous work has focused on the dynamical merger phase, the proposed work here will explore in more detail then ever the long-term post-merger evolution of these systems and the associated ejection and formation of r-process elements in a combination of neutrino-driven and magnetically driven winds from the post-merger remnant neutron star as well as winds from the accretion disk that forms as debris material circularizes around the remnant. This type of post-merger wind could be the dominant site of r-process elements that give rise to a 'blue' kilonova signal in binary neutron-star mergers; the proposed simulations will thus be able to provide answers to the longstanding question regarding the origin of the blue kilonova component in GW170817. On even longer timescales once the remnant neutron-star has collapsed to a black hole, this project will explore whether the accretion disk ejecta in this phase can account for the 'red' kilonova component of GW170817.

Neutron-star–black-hole collisions. This project explores r-process nucleosynthesis in systems with a rotating black-hole. Depending on the magnitude and orientation of the spin vector the accretion streams onto the black hole generated by tidal disruption ('squeezing') of the neutron star will 'warp' and self-intersect. As a result of self-intersection the composition of ejected material changes and produces a 'blue' kilonova instead of what would have been a 'red' kilonova signal in an otherwise equivalent non-spinning/warping system. The color of visible light of a kilonova is indicative of certain groups of r-process elements synthesized. Since 'blue' kilonova signals are traditionally not thougth to be present in such systems, these pioneering simulations will allow us to assess whether GW170817 could have been a neutron-star–black-hole collision in principle.

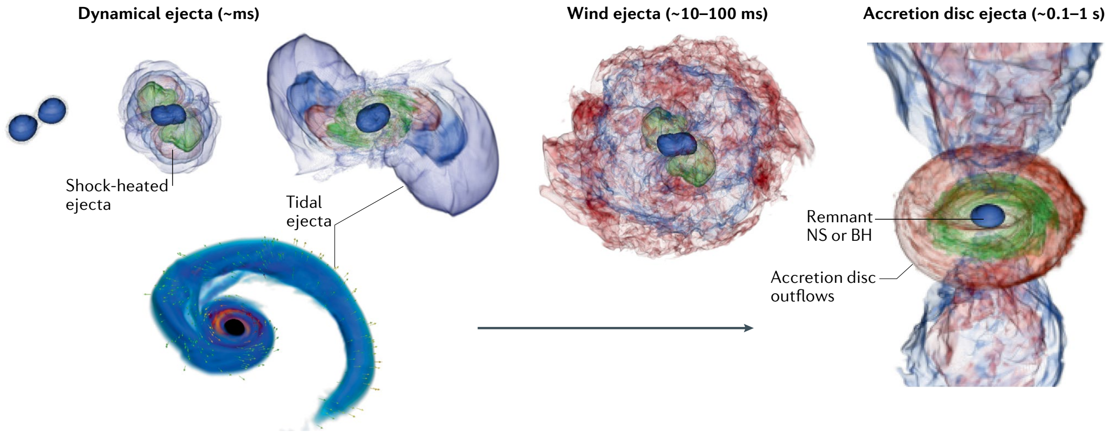

Figure 1: *Overview of the dynamics and ejection of heavy elements from double neutron star collisions (top row) and from neutron-star–black-hole mergers (bottom row). Figure taken in part from our previous work [1]*

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Massive collapsars. Based on the team's previous findings that the collapse of rapidly rotating massive stars can result in the formation of large quantities of r-process elements in outflows from an accretion disk around a black hole due to similar physical processes as in the post-merger phase of neutron-star collisions [2], this project explores r-process nucleosynthesis in accretion disks in the uncharted territory of very massive black holes in the range 100–1000 solar masses. Such accretion disk systems may result from the collapse of very massive, rapidly rotating stars above the so-called pair instability supernova mass gap, from the earliest generation of stars in the universe (so-called Pop. III stars), and from so-called super-massive stars, which may have given birth to the super-massive black holes observed today as 'quasars'. If such objects can produce significant amounts of r-process elements, these simulation results would have broad consequences on our understanding of chemical evolution of the universe.

Proto-neutron stars. A fraction of less than 10% of all isolated neutron stars born as a result of the core-collapse of massive stars at the end of their lives (in a so-called core-collapse supernova) may be rapidly rotating and may possess strong magnetic fields at birth. The initially neutron-rich outflows launched by intense neutrino radiation from the surface of newly born proto-neutron stars that are non-rotating ('the other >90%') were previously shown to unlikely synthesize r-process elements. This is due to the intense neutrino radiation that changes the composition of the outflows in a way that is not conducive of r-process nucleosynthesis. However, strong rotation, as shown in previous work of the project team, as well as strong magnetic fields can, in principle, help accelerate the outflow to keep the composition suitable for the production of r-process elements. This project will explore with pioneering numerical simulations whether the combination of strong rotation and strong magnetic fields can indeed provide the requisite conditions for r-process nucleosynthesis.

Beyond representing pioneering simulations in their own respective field that will lead to qualitatively novel results, the simulation packages described above have broader impact on how the universe chemically evolved from the first generation of stars until today. Expected deliverables such as elemental abundance distributions, ejecta/r-process yields, distributions of ejecta composition etc. from each astrophysical source directly inform modeling of cosmic chemical evolution. The project simulations will also help to develop more detailed models of kilonovae, which will be used in future observations to empirically constrain r-process nucleosynthesis in multimessenger events.

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https://physik.uni-greifswald.de/ag-siegel/

More Information

[1] D. M. Siegel, *Nature Rev. Phys.* **4**, 306–318 (2022). `doi:10.1038/s42254-022-00439-1`

[2] D. M. Siegel, J. Barnes, and B. D. Metzger, *Nature*, **569**, 241–244 (2019). `doi: 10.1038/s41586-019-1136-0`

Project Partners

Perimeter Institute for Theoretical Physics and the University of Guelph, Ontario, Canada

DFG Subject Area

311-01