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The r Process in the Era of Gravitational Waves

Recently, the LIGO and Virgo collaborations have detected the gravitational wave coming from the merging of two neutron stars, now known as GW170817. Such neutron star collisions have long been suggested as possible sites for the creation of the heavy elements such as gold or europium in nature via a nuclear process called the rapid neutron capture process or r-process. With this detection one can for the first time infer an estimate of the frequency of such events in the local universe [1]. Moreover, concerted follow-up observations across the entire electromagnetic spectrum [2] enabled researchers to confirm the theory that merging neutron stars indeed produce and eject into space large amounts of heavy elements.

We implemented the new data into models that track the chemical evolution of our Galaxy from its formation after the Big Bang with a simple composition of mostly hydrogen, helium, and lithium to today's complex mix of chemical elements that are the basis of life and the world as we know it. These chemical evolution models track formation and death of all kinds of stars, including the merging of neutron stars, and the elements they create and eject. In a previous paper [3] prior to the new discovery we reviewed and normalized a wide variety of such chemical evolution studies, including sophisticated cosmological hydrodynamic simulations, and predicted the neutron star merger frequency required, for an assumed amount of elements ejected per event, in a galaxy evolution context to reproduce the r-process enrichment observed in our Galaxy, assuming neutron star mergers are the dominant astrophysical site of the r-process.

We can now test the possibility of neutron star mergers being the main source of r-process elements using the same models with the new data. Figure 1 shows that if GW170817 (pink shaded area) is a typical event, modern chemical evolution calculations (dark blue shaded area) confirm that neutron star mergers can produce enough r-process elements to explain the amount of europium observed in galaxies. Among other elements, we found that GW170817 ejected between 15 and 70 Earth masses of pure gold. This work implies that neutron star mergers are likely to be the dominant r-process site in the universe. In fact, there is an overlap between chemical evolution requirements (what is needed to explain the observed amount of elements), LIGO/Virgo (what is observed in terms of frequency and element production), and population synthesis models (the predicted event frequency). This work represents a massive collaborative effort that connects r-process nucleosynthesis, nuclear physics, multi-wavelength emissions, gravitational waves, binary population synthesis models, stellar abundances observations, and galactic chemical evolution simulations.

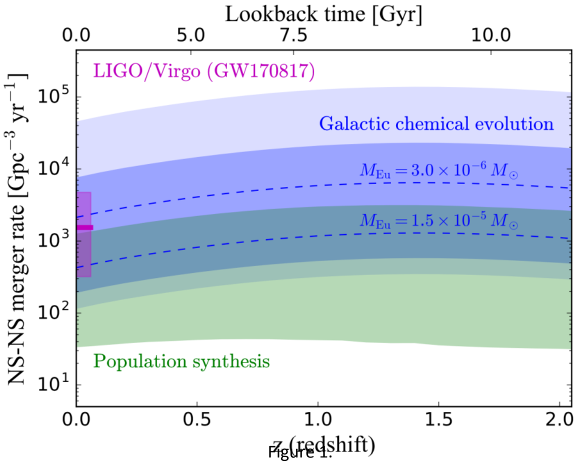

Figure 1.

Evolution of the neutron star merger rate density as a function of redshift. The pink thick horizontal line and shaded area (at low redshift) show the rate and uncertainty measured by LIGO/Virgo. The blue dashed lines show the rates needed in galactic chemical evolution (GCE) studies to reproduce the r-process enrichment observed in the Milky Way using neutron star mergers only. These two lines adopt two different europium ejecta masses per event, representing the lower and upper limits derived for GW170817, assuming a typical r-process abundance pattern. The dark blue shaded area surrounding these two lines represents GCE model uncertainties. When adopting theoretical r-process abundance patterns calculated from first principle, the mass of europium ejected becomes more uncertain due to nuclear physics uncertainties, which enlarges the uncertainty band associated with GCE (lighter blue shaded area). The green shaded area shows the neutron star merger rate densities predicted by population synthesis models that follow theoretically the evolution and interaction of binary stars and their remnants.

Nuclear physics related to rare isotopes is needed to understand which elements are being produced, how they are being made, and what the required conditions deep inside the neutron star collision region are. Our study is the first to directly include the impact of some of the large nuclear uncertainties (lighter blue shaded area) in a galaxy evolution context. These uncertainties will be addressed with experiments planned at future rare isotope facilities such as FRIB.

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[1] LIGO Scientific Collaboration & Virgo Collaboration 2017, Physical Review Letters, 119, 161101
[2] [2] LIGO Scientific Collaboration & Virgo Collaboration 2017, ApJL, 848, 12
[3] B. Côté et al. 2017, ApJ, 836, 230
[4] B. Côté et al. 2017, ApJL, submitted, arXiv:1710.05875