Kilonovae: The Colorful Birth Of The Heaviest Elements In Our Universe

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1 Introduction

The origin of the heaviest elements in the universe is one of the leading mysteries cosmologists and astrophysicists face, until now. Kilonovae are now favored as the main producers of heavy r-process elements. A kilonova, also called a macronova, is powered by the radioactive decay of r-process nuclei synthesized in the ejecta of a binary neutron star (BNS) merger, or a blackhole and neutron star merger (BH-NS) (Abbott et al., 2017[2]). As a significant quantity of neutron-rich radioactive species decay after a NS merger, a faint transient, a kilonova, should be the result. This is an event similar to a faint, short lived supernova. Because NS merger transients peak at a luminosity that is a factor of $\sim 10^3$ higher than a typical nova, Metzger et al. (2010) proposed naming these events 'kilo-novae.' Detailed calculations suggest that the spectra of such kilonova sources will be determined by the heavy r-process ions created in the neutron-rich material (Tanvir et al., 2013). Kilonovae can be red or blue at optical wavelengths based on the components of the ejecta (Metzger & Fernández, 2014). There is a lot more to be discovered about kilonovae; the first multimessenger detection of a BNS merger was only in 2017 via gravitational waves (GWs), short gamma ray bursts (SGRBs), radio waves, and x-rays. This discovery on August 17, 2017 by Advanced LIGO and Advanced VIRGO inferometers, named GW170817, sparked many new investigations in the growing field of research for kilonovae, which are to be discussed later on.

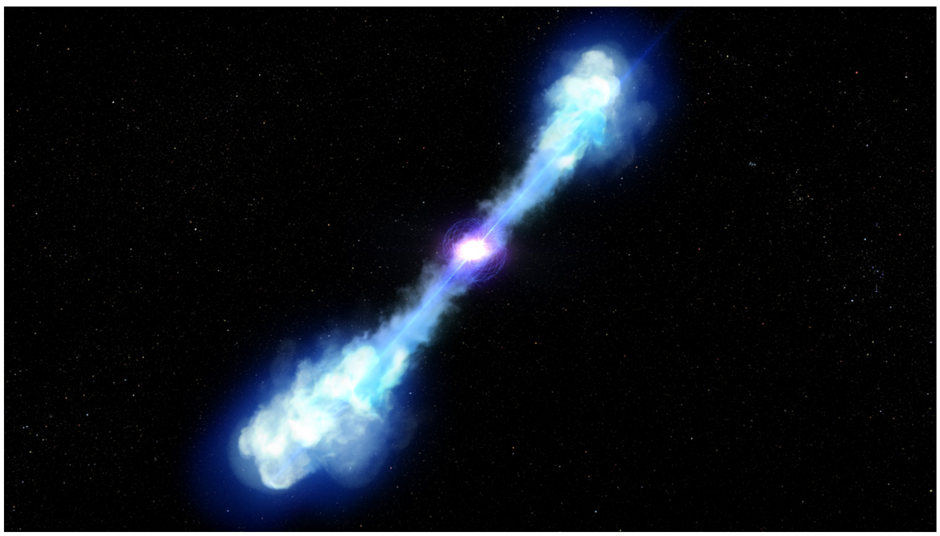

Figure 1: Artist's rendition of two neutron stars colliding to create a kilonova. Image via Center for Astrophysics/ NASA/ ESA/ D. Player (STScI).

1.1 What Happens During NS Mergers?

Neutron stars are the remnants of core collapsed massive stars that did not end up as black holes. NS are extremely dense and have diameters ranging from 10-20 km. In BNS systems, the two bodies can have an inspiral orbit, where they will spiral towards each other over time and eventually merge. As the NSs get closer, they cause GWs. GWs can be described as 'ripples' in space-time that travel in all directions from a major/substantial event (such as a NS merger) at the speed of light.

Gravitational waves do not imply that a merger contains two NSs. The detection of EM emission, however, does imply that at least one of the merging compact objects is a NS. But detecting GWs are important for determining the spatial distribution of the merger events. GWs also aid in determining the location of such events. Furthermore, knowing the host galaxy of a merger is useful for comparing the redshift of the event to the galaxy, in order to further determine the propagation of the kilonova.

SGRBs are cosmic flashes of gamma-rays (γ-rays) (Klebesadel et al., 1973) with durations of less than 2 seconds. It's been widely accepted since the 1990s that NS and NS-BH mergers were the producers of SGRB, and the theory was heavily supported with later observations. SGRBs are commonly believed to be powered by the accretion of a massive remnant disk onto the compact BH or NS remnant following a merger. This is typically expected to occur within seconds of the GW detection, making their association with the GWs very evident (since the γ-ray sky is otherwise quiet). More studies will need to be conducted to definitively determine what causes these short bursts.

Following the GWs and SGRBs, a kilonova occurs, powered by the decay of the radioactive r-process material that emerges following the collision of the BNSs or BH and NS. A major theoretical breakthrough was introduced from considerations of the opacities of lanthanide elements, which are copiously produced by the strong r-process (Kasen et al., 2013). Lanthanides are elements of the lanthanide series on the periodic table, shown as elements 58 through 71. Lanthanides are also known as 4f elements because they have incompletely filled 4f subshells. Atoms and ions like this whose valence electrons partially fill the f-shell have a substantially larger number of low-lying energy levels and bound–bound transitions available to them compared to iron-peak elements. This dramatically increases the opacity of lanthanide-rich material at optical wavelengths. This increase in opacity delays and lowers the peak luminosity of a kilonova and pushes the flux to emerge in the near-infrared (NIR), which is referred to as a red kilonova (Barnes & Kasen, 2013; Kasen et al., 2013; Tanaka & Hotokezaka, 2013). Later, it was realized that lanthanide-poor material ejected with a high electron fraction (Ye), potentially from polar dynamical ejecta or winds, could produce a blue kilonova that dominates the optical emission (Metzger & Fernández, 2014). These colorful transients can last days to weeks.

1.1.1 Sequence of Events

A solid prediction from numerical simulations is that a NS merger site is surrounded by some baryon contaminated region with large mass (at least 0.01 solar masses). Baryons are a type of composite subatomic particle that contains an odd number of valence quarks; protons and neutrons are the most stable type of baryon. The kilonova begins as NSs or a BH and a NS merge. An SGRB-like jet launched by the merger would have to pierce through these baryon outflows of material before breaking out. The jet propagation (direction) within the BNS ejecta is a critical step that shapes the jet's final angular structure, which then determines its ultimate fate: successful versus choked (reviewed by Abbot et al. 2017). While advancing through the ejecta, the jet dissipates energy into a hot cocoon (a wide-angle outflow constituted of shocked jet and ejecta material), which expands relativistically after breaking out of the ejecta. Numerical simulations suggest that for standard parameters of successful jets, the time the jet spends within the BNS ejecta is comparable with the duration of the subsequent SGRB γ-ray emission. This implies that the cocoon energy and the γ-ray burst (GRB) energy are expected to be similar. Just like the jet, the cocoon has clear EM signatures associated with it, including cocoon breakout γ-ray emission, ultraviolet (UV) cooling emission, radioactive heating, and a broadband afterglow. Many cocoon observational signatures still remain elusive. Hamidani & Ioka (2022) argues that the cocoon emission can be used to identify NS mergers and SGRBs differently, such as even in cases where the jet has failed or is viewed off-axis (see models by Hamidani & Ioka, 2022). This can bring additional information on the merger process (such as the ejecta mass), on SGRBs (their jets and the central engine), and on kilonovae (r-process nucleosynthesis and nuclear composition at early times).

1.2 Biggest Breakthrough So Far

GW170817 was produced by the merger of two neutron stars in the galaxy NGC4993 (see Figure 2), followed by a SGRB and a kilonova (Abbott et al., 2017[2]). This GW signal was detected as a compact binary merger by Advanced LIGO and Advanced Virgo on August 17, 2017, with $\sim$100 seconds of GW emission detectable in the LIGO band leading up to the union of the two objects, in this case BNS (Abbott et al., 2017[1]). This event was followed 1.74$\pm$0.05 seconds later by a burst of γ-rays detected by the Fermi

Gamma-ray Burst Monitor (Fermi-GBM) (Goldstein et al. 2017) and INTEGRAL SPI-ACS (the anti-coincidence system of spectrometer SPI on the International Gamma-Ray Astrophysics Laboratory) (Savchenko et al., 2017). The subsequent detection of an optical counterpart to GW170817 and GRB 170817A was first made by the One-Meter Two-Hemispheres collaboration using the Swope Telescope at 10.9 h after the merger (Coulter et al., 2017). Within the next hour, five other teams independently detected the same source, now known as AT 2017gfo (Coulter et al., 2017), a kilonova! No X-ray or radio counterpart was detected down to deep limits during the first few days of observations (Margutti & Chornock, 2021; Savchenko et al., 2017). A rising X-ray and radio source eventually crossed the threshold of detection of sensitive X-ray and radio observatories. The Chandra X-ray Observatory detected signals on day 8.9 (Troja et al., 2017), and the VLA (Very Large Array) measured radio signals on day 16.4 (Hallinan et al., 2017). This event became the first multi-messenger detection of NS mergers, which will open many doors to new discoveries about mergers and kilonovae now that there is data to analyze from multiple electromagnetic (EM) wavelengths.

The multicolored kilonova, AT 2017gfo, dominated the optical spectrum for several weeks after the merger. This transient appeared in the UV, optical, and infrared, which allowed for the identification of the host galaxy and proved association with the aftermath of the BNS. Although the ultimate fate of the merger remnant cannot be probed directly, indirect evidence favors a BH (Abbott et al., 2017[2]).

1.3 Questions

1. What are the heaviest r-process elements that can be produced during a kilonova?

   The comparison of the observed spectroscopic and photometric data to theory models only confirmed the existence of heavy elements with high atomic opacity, likely lanthanides, as well as the potential signature of lighter r-process elements such as strontium. Whether or not even heavier nuclear isotopes, the actinides, can be produced in BNSM events remain unclear (Wu & Banerjee, 2022). Actinides are elements on the periodic table numbered 89-103, whose origins remain unknown. With improved models and observations of kilonovae, it is expected that the elements produced will become known for certain.

Figure 2: Observations of the GW170817 kilonova by Hubble over a ∼week-long span. Gravitational waves detected by Advanced Ligo and Advanced Virgo revealed the location of the event to be in upper left quadrant of the galaxy NGC4993 (ESA/Hubble)

2. Are kilonovae affecting the Hubble Constant?

   Significant theoretical modeling prior to and after GW170817 has made it possible to study AT2017gfo in great detail, including measurements of the masses, velocities, and compositions of the different ejecta types. It is still a question if kilonovae luminosities are standardized, but, if so, this could lead to a potentially reliable way of measuring the expansion rate of the universe. Coughlin et al. (2020) outlines that the idea for measuring the Hubble constant H_0 is to use techniques borrowed from the type-Ia supernovae (SNe) community to measure distance moduli based on kilonova light curves. Light-curve flux and color evolution are used, which do not depend on the overall luminosity, compared to kilonova models, to predict the luminosity. And when combined with the measured brightness, the distance is constrained. A model can then be developed for the innate luminosity of kilonovae based on observables, such that the luminosity can be standardized. Given the potential of multiple components and the change in color depending on the lanthanide fraction, it is convenient to use kilonova models to perform the standardization. This assumption will be testable when a sufficiently large sample of high-quality kilonovae observations are available.

3. How will differing end results of mergers affect the subsequent kilonova?

   Metzger (2017) provides a hypothesis for low mass BNS mergers; such mergers may produce stable magnetars that substantially enhance the kilonova luminosity. Conversely, with higher mass binaries, the magnetar lifetime is very short and its impact on the kilonova is negligible. It's unknown exactly what would happen with other merger results, such as from BH-NS, or NS-NS that may not produce magnetars. The first step to understanding the effect these events have on kilonovae would be to know the end result of said mergers. It is not yet known what the ultimate outcome of such events are, or what parameters would affect the outcome, such as mass of the NSs, period, density, etc. With this knowledge, the luminosity of certain kilonovae, or elements created during one, may be more easily discernible.

1.4 Why Is This Important?

Understanding kilonovae will allow us to finally determine where the heaviest r-process elements originate from. Lanthanides and possibly even anticides are the suspected creations, some of the heaviest and rare elements we know of! We'll be able to update cosmological studies and confirm hypotheses that NS mergers are responsible for these elements, all while gaining an appreciation of the universe for creating these elements we are very familiar with.

More observations of kilonovae may even provide a firmer grasp on the Hubble Constant (H_0). The GWs that are emitted before the kilonova occurs, or the possible standard luminosity of kilonova, may be new ways of measuring the rate of expansion of the universe, but many more considerations must be taken into account before these are reliable ways for measuring H0. Further research in this field is sure to mark a new era in multi-messenger, time-domain astronomy.

1.5 What Now?

After the GW discovery of 2017, many organizations created paths for continued observations of NS mergers and further research of kilonovae. With an ongoing dedicated effort, as more detections or constraints on kilonovae become possible over the next few years, we will be in an excellent position to use these observations to probe the physics of BNS mergers, their remnants, and their role as an origin of the r -process. As models of kilonovae improve, more theories and observational proposals will arise in order to fully understand this fascinating astronomical event. Mathematical models will be tweaked when new information arises, to better measure the Hubble Constant, and determine if kilonovae are indeed standardizable. The field of research for kilonovae is a promising path to choose in terms of discoveries to be made; be sure to keep kilonovae exploration on your radar.

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