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The Physics of Kilonovae

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The science returns of gravitational wave astronomy will be maximized if electromagnetic counterparts to gravitational-wave sources can be identified. Kilonovae are promising counterparts to compact binary mergers, both because their long timescales and approximately isotropic emission make them relatively easy to observe, and because they offer astronomers a unique opportunity to probe astrophysical heavy-element nucleosynthesis and merger-driven mass ejection. In the following, I review progress in theoretical modeling that underpinned advances in our understanding of kilonovae leading up the first detection of a neutron star merger, GW170817. I then review the important lessons from this event and discuss the challenges and opportunities that await us in the future.

Keywords: gravitational wave astronomy, kilonovae, kilonovae: TNS 2017 gfo, DLT17ck, SSS17a, r-process nucleosynthesis, neutron star binaries

1. INTRODUCTION

Multi-messenger astronomy refers to the revolutionary possibility of combining electromagnetic (EM) and gravitational-wave (GW) observations to gain new insight into astrophysical phenomena. In the current era of ground-based gravitational-wave detectors, the mergers of compact objects—black holes (BHs) and neutron stars (NSs)—are the systems most accessible to multi-messenger astronomy, and their routine observation promises to teach us more about stellar binary evolution, dynamics in the strong gravity regime, the production and evolution of astrophysical jets, the NS equation of state (EOS), and the origin of the heavy elements. Among mergers' EM counterparts, "kilonovae," radioactively-powered, quasi-isotropic transients that shine at optical and infrared wavelengths and evolve on timescales of days to weeks, are unique in their ability to shed light on merger-driven mass ejection and nucleosynthesis.

2. BACKGROUND ON *R*-PROCESS TRANSIENTS

The idea that compact object mergers produce radioactively-powered EM emission in addition to gravitational wave signals is rooted in the realization [1–3] that mergers could synthesize unstable nuclei whose decays would power an electromagnetic transient [4].

More specifically, the partial disruption of a NS in a NS[2] or NSBH merger produces a neutron-rich outflow capable of assembling a broad range of heavy, unstable nuclei via rapid neutron capture, or the *r*-process. As first outlined by [5] and [6], the *r*-process occurs in explosive environments featuring a high flux of free neutrons, which allows successive captures of free neutrons onto light seed nuclei on timescales shorter than typical β-decay lifetimes. This drives the composition of the gas toward heavy, neutron-rich regions of the chart of the nuclides, in many cases close to the neutron drip line. When neutron capture ceases, the newly-born nuclei decay toward stability, producing an abundance pattern with characteristic peaks around mass numbers $A = 82, 130, 196$. The stable and long-lived daughters account for about half of the elements in the Periodic Table more massive than Iron.

FIGURE 1 | The impact of nuclear physics and astrophysical uncertainties on predicted *r*-process abundances. The reference case (black curve) was calculated using the FRDM mass model [15] for a low-entropy, neutron-rich gas. Every other curve differs from the reference case in only one way. The **orange** curve shows the impact of decreasing the expansion time, while the purple curve demonstrates the much stronger effect of raising Y_e. The influence of the choice of nuclear mass model is illustrated by the **light blue** curve. **Scaled solar *r*-process abundances from [16] are plotted as black diamonds.** This figure was adapted from Figure 1 of [17] with permission from J. Barnes.
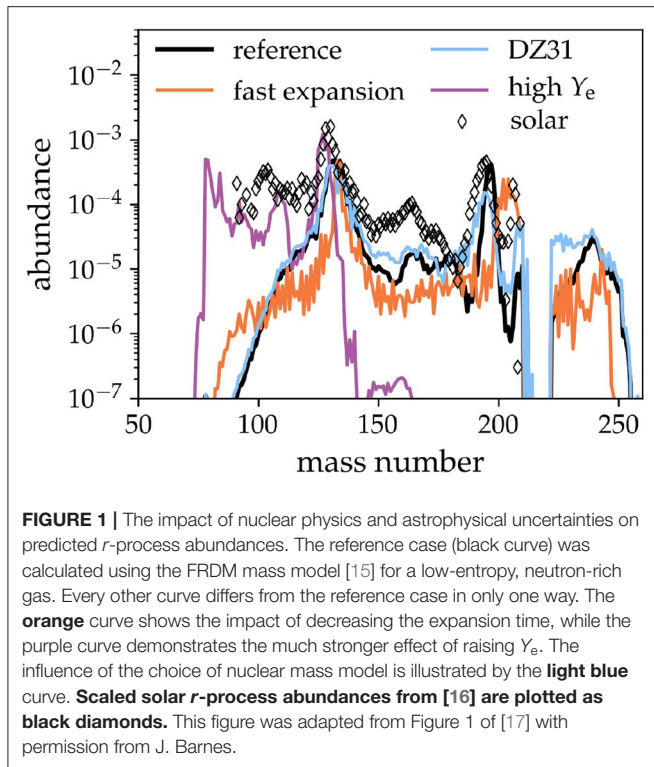
The complexity of *r*-process nucleosynthesis allows for variation in the final abundance pattern. While a lack of relevant experimental data (e.g., nuclear masses and neutron-capture cross sections) for many nuclei involved in the *r*-process present a challenge for theoretical *r*-process simulations [7, 8], even if nuclear physics uncertainties were eliminated, abundance yields would still be sensitive to conditions when nucleosynthesis begins. Traditionally [9, e.g.], gasses with the potential to undergo an *r*-process have been parametrized in terms of three variables: expansion timescale (τ_{exp}), entropy per baryon (s_B), and initial electron fraction (Y_e), which is defined as the number of protons per baryon and quantifies the relative number of free neutrons available to build up heavy nuclei.

The final abundance pattern depends on the interplay of all these factors [e.g., [10]]. However, for conditions expected for compact object mergers (i.e., neutron-rich, low-entropy gasses), abundances appear from simulations to be particularly sensitive to Y_e, with $Y_e \approx 0.25$ emerging as a threshold above which the *r*-process fails to burn nuclei beyond the second *r*-peak [11, 12]. Such a truncated *r*-process is termed a "light" *r*-process, as opposed to the "heavy" *r*-process, which takes place under very neutron-rich conditions and synthesizes stable and semi-stable nuclei up to $A \sim 260$. In a merger, the NS material that forms the expanding gas is very neutron rich [13], and will remain so unless weak-current interactions are strong enough to push the composition toward a more moderate Y_e [14]. The potential for *r*-process variability is illustrated in **Figure 1**.

The role of *r*-process nucleosynthesis and decay in generating EM signals associated with compact object mergers was first discussed by [4], who derived the earliest theoretical model of *r*-process-powered transient emission. Since this groundbreaking work, the community has undertaken increasingly detailed studies of all the major parameters governing the nature of *r*-process transients, from the energy supplied by the *r*-process, to the ejected mass, to the optical properties of *r*-process atoms and ions.
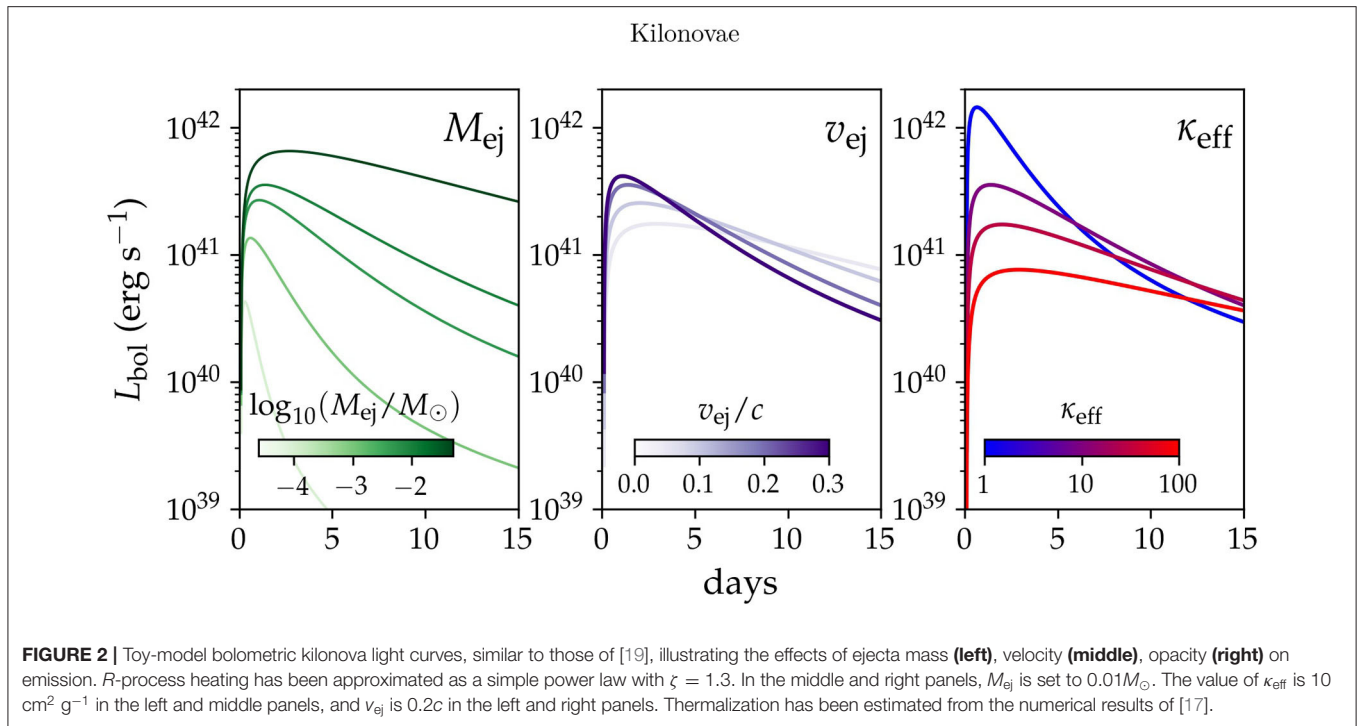
3. KEY PARAMETERS

While detailed computational models are required to fully explain the evolution of radioactive astrophysical transients, the basic character of these systems are functions of a few physical parameters whose relationships to the emission can be understood from basic physical principles.

In simple (semi-)analytic models [à la, [18]], a transient's luminosity peaks when the expansion time t equals the timescale for photons to diffuse through the ejecta, $t_{diff} \propto (M_{ej}\kappa/v)^{1/2}$, where M_{ej} and v_{ej} are the mass and characteristic velocity of the ejecta, respectively, and κ is its effective opacity. The luminosity at peak is roughly equivalent to the instantaneous rate at which radioactive decay is heating the ejecta. This correspondence reappears on the tail of the light curve, when the ejecta is mostly transparent and the luminosity directly reflects radioactive heating. Consideration of the above reveals that the energy released (per unit mass) in the radioactive decays of *r*-process nuclei is a crucial determinant of kilonova emission, as are the mass, velocity, and opacity of merger-driven outflows. The effects of these parameters on kilonovae's bolometric light curves **are** presented in **Figure 2**.

3.1. *R*-Process Heating and Radioactivity

The dominant decay channel for unstable *r*-process nuclei is β-decay [$(Z, N) \rightarrow (Z+1, N-1)$; [20]], which emits high-energy β-particles, neutrinos, and γ-rays. In most realizations of the *r*-process, select nuclei will also undergo α-decay ($(Z, N) \rightarrow (Z-2, N-2)$) and fission, releasing energy in the form of more massive α-particles and fission fragments. [17, 21–23]. These suprathermal particles and photons transfer heat the ejecta as they interact with it, and the thermal photons produced by the heated gas diffuse outward to form the light curve. The emerging luminosity, as well as the relationship between luminosity and ejected mass, depend both on the rate at which the *r*-process produces energy and the efficiency with which that energy is converted to thermal photons.

When [4] constructed the first kilonova models, they treated the overall normalization of energy from *r*-process decay as a free parameter proportional to the rest mass energy of the ejected material. In other words, the sum of all the energy released from radioactivity was taken to equal $fM_{ej}c^2$, with f allowed to vary. Despite this simplification, their model of the *r*-process uncovered what turned out to be a robust feature of *r*-process radioactivity. By assuming the lifetimes τ of decaying nuclei were evenly distributed logarithmically and ignoring the correlation between τ and decay energy, Li et al. [4] calculated that *r*-process decay should release energy like $\dot{E}_{rad} \propto 1/t$. More rigorous calculations using full *r*-process nuclear reaction networks [20,

FIGURE 2 | Toy-model bolometric kilonova light curves, similar to those of [19], illustrating the effects of ejecta mass **(left)**, velocity **(middle)**, opacity **(right)** on emission. *R*-process heating has been approximated as a simple power law with $\zeta = 1.3$. In the middle and right panels, M_{ej} is set to $0.01 M_\odot$. The value of κ_{eff} is 10 cm^2 g^{-1} in the left and middle panels, and v_{ej} is $0.2c$ in the left and right panels. Thermalization has been estimated from the numerical results of [17].

24, 25] as well as more robust analytic treatments [26] modified this picture, finding that, when heating is dominated by the β-decays of a broad ensemble of nuclei, the energy production is well-approximated by a steeper power-law, $\dot{E}_{rad} \propto t^{-\zeta}$ with $\zeta = 1.2 - 1.4$.

However, while power-law heating is a useful model, uncertainties in *r*-process calculations resulting from unmeasured quantities, as well as the sensitivity of the *r*-process to its astrophysical environment, leave room for variability in nucleosynthesis and decay, and therefore $\dot{E}_{rad}$. In particular, the behavior of $\dot{E}_{rad}$ is likely to deviate from a power-law if α-decay or fission becomes dominant over β-decay, or if only a small number of nuclei are contributing to the heating [22, 23, 27].

More detailed nuclear calculations also revealed the absolute scale of the energy released by *r*-process decay, allowing [20] to predict that the peak luminosity of transients from NS^2 mergers would be about a thousand time brighter than a classical nova, motivating the term "kilonova."

Metzger et al. [20] was also the first to estimate the fraction of the energy from *r*-process decay able to effectively heat the gas (the "thermalization fraction"). More detailed numerical work on thermalization was carried out by [17], who found that thermalization increased for denser ejecta configurations, lower-energy decay spectra, and radioactivity profiles that favored α-decay or fission relative to β-decay. These themes were revisted in [28]. Later analytic work [27, 29], showed that thermalization also depends on how the decay spectrum and $\dot{E}_{rad}$ evolve with time. The potential variation in *r*-process heating [see e.g., [23]], and the sensitivity of the thermalization efficiency to that variation, suggest that further detailed numerical studies may be useful

for understanding the true allowed range of kilonova heating and luminosity.

3.2. Mass Ejection

There are three main channels through which merging compact objects ejecta mass [see reviews by [30, 31]]. All produce an outflow neutron rich enough to support at least a light *r*-process.

High-velocity *tidally shredded* outflows are produced during the final stages of inspiral when a NS is disrupted by the differential gravitational field of its binary companion. While the quantity of ejected mass depends on the NS EOS (less compact EOSs are more easily shredded) as well as the mass ratio of the binary and the spins of the component stars [32–35], it is generally expected to be small [$\sim 10^{-4} M_\odot$; [36, 37]] for a NS^2 merger, though it can be substantially larger ($\sim 0.1 M_\odot$) for a NSBH merger provided the NS disrupts outside the innermost stable circular orbit [38, 39]. Tidal shredding produces a cold, low-entropy outflow with an abundance of free neutrons. It is therefore expected to undergo a robust *r*-process with nucleosynthesis beyond the third peak [e.g., [13]].

In contrast, *dynamically squeezed* matter is subject to enough weak interactions to inhibit the synthesis of the heaviest elements. Dynamical squeezing occurs when merging NSs finally collide [36, 37, 40]. The violence of the collision expels material from the contact interface via shocks, which accelerate the resulting outflow to high velocities and heat it to high temperatures, allowing the production of thermal electron/positron pairs and neutrinos. Absorption of these particles then raises the Y_e of the gas [41, 42].

The mass of this component increases with NS compactness [36], since NSs with smaller radii make contact at a smaller separation, and therefore a higher velocity, leading to more energetic collisions capable of unbinding more matter (this trend holds only up to a point; mass ejection is minimal if the colliding NSs are compact enough to collapse promptly to a BH [43], though mass asymmetry can offset this effect [37]).

Some simulations [36, 44] suggest that, in certain cases, this outflow will feature a high-velocity, low-mass ($\sim 10^{-5} M_{\odot}$) tail of material whose rapid expansion hinders neutron capture, resulting in a composition dominated by lighter nucei and leftover free neutrons [21]. Under such conditions, the free-neutron decay could power a short-lived transient peaking on timescales close to the free-neutron half life [45].

The most robust mass ejection channel may be **winds from accretion disks** surrounding the mergers' central remnants (CRs). In NSBH mergers, the disk is formed from disrupted NS matter that remains gravitationally bound. For NS^2 mergers, the primary source of disk material is a NS CR, which pushes material off its surface as it transitions from differential to solid-body rotation [46] (The prompt collapse of a CR therefore inhibits disk formation for NS^2 mergers.) Disk material is unbound through some combination of viscous heating [47], magnetic turbulence [48], α-recombination [49], and ν-absorption [50, 51].

The effect of weak interactions on the disk composition is uncertain, and likely depends strongly on the CR. While a central NS would be strong source of neutrinos [e.g., [52]], a central BH would not be; in the latter case, weak interactions in the disk would be limited to those driven by thermal neutrinos and positrons produced by the disk itself [53]. Many studies [48, 54, 55] have found that, for a BH CR, the accretion disk regulates its composition to a low Y_e, though the exact distribution of Y_e appears to be sensitive to the neutrino transport method adopted [e.g., [56]].

As with other mass ejection methods, the mass of the disk (and therefore the disk wind) depends on the binary parameters and NS EOS [e.g., [40]]. Less compact NS EOSs produce more massive disks, and therefore more massive disk outflows. The EOS also affects the composition (at least for NS^2 mergers) by controlling the fate of the CR, and the exposure of the disk to neutrino irradiation [57–59].

3.3. Opacity

The distinct compositions burned in the various outflows generated in NS^2 and NSBH mergers have major effects on kilonova emission because the composition of the gas determines the opacity of the ejecta, which in turn influences the light curve and the spectral energy distribution (SED).

As the gas expands, it cools to temperatures ($\sim$few $\times 10^3$ K) that support low levels of ionization. Under these conditions, the dominant source of opacity is bound-bound ("line") opacity [60]. In the bound-bound regime, the absorption of photons by atoms results not in ionization, but in the excitation of its bound electrons to a higher-energy configuration. While the probability that any *particular* absorption will occur is a function of the many-body quantum mechanics governing the absorbing atom, the effective *continuum* opacity depends on the number of opportunities for a photon of a given energy to suffer an absorption—i.e., on the density of moderate to strong lines in wavelength space.

Determining bound-bound opacity is particularly challenging for *r*-process compositions, since there is limited experimental data on energy levels and absorption probabilities for many of the species burned by the *r*-process. Nevertheless, general trends can be deduced from simple heuristics. First, the more unique species are present in a composition, the greater the number of lines, and the higher the opacity. Second, and more significantly, the presence of atomic species with a high degree of complexity (i.e., with a greater number of distinct electronic configurations) will increase opacity.

Atomic complexity is a function of the size of an atom's valence electron shell. A valence shell that accommodates a larger number of electrons allows for more distinct electronic configurations; each configuration has a slightly different energy, so the net effect is a greater number of energy levels, more transitions between energy levels, and a higher opacity [see e.g., [61]]. This picture has been borne out both by available experimental data [62] and by atomic structure calculations, with groups using different atomic structure modeling codes all finding a striking increase in opacity as valence shell size increases [61, 63, 64].

The relationship between atomic complexity and opacity has profound implications for kilonovae. Lanthanides and actinides are the most complex elements in the Periodic Table. These species have a high number of closely spaced energy levels, resulting in an abundance of low-energy bound-bound transitions and a high opacity that extends out into the near infrared (NIR). While lanthanides and actinides are easily synthesized by the heavy *r*-process, they are produced in negligible quantities in a light *r*-process event [11, 12]. The opacity of the kilonova ejecta—and the color of its emission—therefore depend sensitively on the nucleosynthesis that took place in its ejecta.

As first explained in [65], the high opacity of a lanthanide-rich (heavy *r*-process) ejecta delays and dims the light curve peak, while the extreme density of lines at optical wavelengths pushes the emission redward, causing the spectrum to peak in the NIR [see also [62]]. Of course, not all outflows from compact object mergers will undergo a heavy *r*-process. Light *r*-process compositions, will have a lower opacity. The emission associated with these outflows will have a faster rise; a sharper, brighter light-curve peak; and an SED concentrated at blue/optical wavelengths, similar to the original predictions of [20].

Kilonova emission may be due to a combination of signals from multiple outflows characterized by different histories of nucleosynthesis: a "red" component associated with a lanthanide-rich outflow, and a "blue" component from a composition that failed to burn lanthanides [58, 65]. The outcome of the *r*-process is closely tied to the manner of mass ejection and, in the case of disk winds, the nature or lifetime of the CR. The presence or relative prominence of red or blue kilonova components can therefore reveal the mass ejection mechanisms at play, and even shine an (indirect) light on the NS EOS.

4. LESSONS FROM GW170817

The theory outlined above was established before a compact object merger was definitively detected, but was corroborated by the first such detection. On August 17, 2017, the LIGO*-Virgo network picked up a signal consistent with the inspiral of a merging neutron star binary [66]. A spatially-coincident short-gamma ray burst was observed contemporaneously [67–69], increasing confidence in the signal and triggering a worldwide search by observational astronomers for a radioactive counterpart, which was soon identified in a galaxy a mere 40 Mpc distant [70–77]. These observations yielded a wealth of data which, in combination with theory, crystallized into a fairly coherent picture of the post-merger system.

The bolometric light-curve evolution was consistent with an approximately power-law injection of energy, as expected from the decay of a large ensemble of r-process nuclei [78]. The transient's broadband evolution showed signs of two distinct components, with the blue and optical bands rising to an early peak and declining swiftly thereafter, while emission in the redder bands evolved on a much longer ($\sim$2 week) timescale [e.g., [70, 72, 72, 78, 79]]. The disparate behavior at red and blue wavelengths was interpreted by most groups [72, 80–82] to require two separate outflows [but see [83]]: a lanthanide-poor one driving the early blue component, and a lanthanide-rich one powering the extended red and NIR emission.

Since long-lived red emission is difficult to explain without invoking the uniquely high opacity of the lanthanides and actinides produced in abundance by the heavy r-process [84, 85], the broadband light curves confirmed that GW170817 had indeed triggered r-process nucleosynthesis, and that its optical counterpart was in fact a kilonova.

The identification of kilonova spectral features with particular r-process ions would further corroborate this conclusion, and early work on GW170817 demonstrated the promise of such an approach. For example, [86] linked one feature of the kilonova spectrum to singly-ionized Strontium, thus claiming the first detection of an individual r-process element in an electromagnetic transient. Future studies of kilonova spectra will increase confidence in such identifications and improve our ability to constrain compositions from spectral analysis.

In the meantime, kilonova spectra encode information critical for a rigorous reconstruction of the outflow(s) that produced their electromagnetic emission. The spectrum of the GW170817 kilonova was originally dominated by a smooth blue blackbody [73, 87–89], which was replaced after a few days by pseudo-blackbody peaking in the NIR and exhibiting broad absorption features [74, 90]. While the dramatic shift from blue to redder wavelengths is consistent with the kilonova's broadband evolution, the spectrum provided additional information on the velocities of the outflows associated with each component of the emission. The lack of features in the blue spectrum suggested velocities high enough to smooth out any absorption lines, $v_{\rm ej} \sim 0.3c$ [e.g., [73, 80]]. In contrast, the broad absorption troughs in the red spectrum indicate a slower outflow with $v_{\rm ej} \sim 0.1c$.

The combination of spectral and photometric data suggested that the merger launched a high-velocity, lanthanide-poor outflow in addition to a lower-velocity outflow rich in lanthanides. Some authors [e.g., [80, 85, 87]] have attributed the "blue" component to shock-heated, dynamically "squeezed" ejecta. However, the mass required to explain the luminosity ($M_{\rm blue} \approx 0.01 M_\odot$) is higher than predicted by numerical relativity simulations [36, 37, 41, 91], motivating others to consider alternate scenarios [92, 93].

The kilonova's red component has been somewhat more securely associated with a wind unbound from the accretion disk surrounding the CR. The mass ($M_{\rm red} \approx 0.04 M_\odot$ and velocity inferred for this component are consistent with expectations from simulations [48, 55], and the conditions in the disk are thought to be favorable for heavy r-process nucleosynthesis as long as the CR collapses instantly to a BH or survives for only a limited time as a hyper- or supramassive NS [although see [56] for an illustration of the how the treatment of neutrino transport in disks can alter the predicted nucleosynthetis].

5. OPEN QUESTIONS AND A LOOK TO THE FUTURE

GW170817 allowed the astronomy community to make inroads on some of most pressing questions multimessenger astronomy promises to help untangle. First, it demonstrated a long-theorized [94–99] association between short gamma-ray bursts and compact object mergers. Second, it allowed the derivation of the first multi-messenger constraints on the NS EOS [e.g. [100, 101]]. It also allowed an entirely original and independent calculation of the Hubble Constant H_0 [102, 103]. Finally, it conclusively identified mergers as an astrophysical site of r-process nucleosynthesis [70, 72, 80, 90, among many others]. However, the mysteries surrounding mergers and post-merger phenomena are far from resolved.

One major remaining question is related to the source of the blue kilonova component. While the emission seems to be powered by radioactivity, the NS EOS required to produce such a massive outflow via dynamical squeezing is seemingly too compact to *simultaneously* explain the similarly high mass of the red disk wind component. (Recall that disk wind represents a fraction of the total disk mass, and that less compact EOS's favor heavier accretion disks.) Further observations of kilonovae, especially at early times, will be instrumental in revealing the nature of the blue component and providing additional tools for evaluating the NS EOS [104].

A second question is the role of mergers in astrophysical r-process production. GW170817 proved that NS[2] mergers are *a* site of the r-process nucleosynthesis, and simple estimates suggest that the entire r-process content of the Universe may originate in compact object mergers [80, 105]. However, these arguments hinge on the (still very uncertain) merger rates and average r-process mass per event, not to mention the largely unconstrained contribution from NSBH mergers.

In addition to these uncertainties, there are concerns about whether mergers can explain r-process enrichment everywhere it is observed [106]. For example, r-process-enriched extremely metal poor stars seem to require an early-Universe source of the

r-process, while mergers typically occur at a delay of hundreds of millions or even billions of years relative to star formation [e.g., 107]. Likewise, it is difficult to explain enrichment in ultra-faint dwarf galaxies [108] with mergers, given that the velocities pre-merger binaries acquire when their component stars go supernova generally exceed the low escape velocities of these low-mass galaxies [109]. A variety of alternative r-process sites have been proposed [110–113]; however, a complete census of merging systems will clarify rates and ejected mass, and illuminate the role of mergers in burning the heaviest elements.

Additional observations will also unveil the full diversity of merging systems and kilonovae (this is an especially enticing prospect given how distinct the second NS^2 merger, GW190425, was from the first [114]). Neutron star-black hole (NSBH) mergers, which have not yet been observed, should provide an additional source of heterogeneity, as they are expected to produce ejecta that is more massive [32], more neutron-rich [115], and less isotropic [39] than a typical NS^2 merger. There is also likely to be substantial diversity *among* kilonovae from NSBH mergers, since mass ejection is sensitive to parameters such as mass ratio and component star spin [e.g., [116]]. Observations of NSBH mergers and their kilonovae are therefore crucial for documenting the full range of compact objects mergers' radioactively powered EM emission.

We can hope, in the next several years, to better constrain merger rates, and to understand how merging systems are distributed by total binary mass, mass ratio, and binary type (NS^2 v. NSBH). We can map out the relationship between binary and kilonova parameters, a map that will become increasingly accurate as parallel advances and theory and nuclear physics experiment (e.g., the Facility for Rare Isotopes Beams; [117]) allow us to more confidently infer ejected mass from observations. We can determine how common various components are (and we can hope to observe as-yet unseen components, like tidal tails or neutron precursors) and assess whether the net enrichment from these components is consistent observed stellar r-process abundances (and variations in those abundances). Ideally, we will develop the tools to measure or constrain abundance yields from the spectra of individual merger events. Our deeper understanding of kilonovae will allow us to confidently progress on the questions—r-process origins, NS EOS, H_0—that multi-messenger astronomy is uniquely well-poised to address.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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