Full Transport Model of GW170817-Like Disk Produces a Blue Kilonova

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The 2017 detection of the inspiral and merger of two neutron stars in gravitational waves and gamma rays was accompanied by a quickly-reddening transient. Such a transient was predicted to occur following a rapid neutron capture (r-process) nucleosynthesis event, which synthesizes neutron-rich, radioactive nuclei and can take place in both dynamical ejecta and in the wind driven off the accretion torus formed after a neutron star merger. We present the first three-dimensional general relativistic, full transport neutrino radiation magnetohydrodynamics (GRRMHD) simulations of the black hole-accretion disk-wind system produced by the GW170817 merger. We show that the small but non-negligible optical depths lead to neutrino transport globally coupling the disk electron fraction, which we capture by solving the transport equation with a Monte Carlo method. The resulting absorption drives up the electron fraction in a structured, continuous outflow, with electron fraction as high as \( Y_e \sim 0.4 \) in the extreme polar region. We show via nuclear reaction network and radiative transfer calculations that nucleosynthesis in the disk wind will produce a blue kilonova.

Introduction—In August, 2017, the inspiral and merger of a pair of neutron stars (GW170817) was jointly detected by gravitational wave detectors and electromagnetic telescopes around the world [1]. This detection confirms that such mergers are central engines of short gamma ray bursts [2–4] and a site of r-process nucleosynthesis [5], where the heaviest elements in our universe are formed [6–9].

The radioactive decay of r-process elements produces an optical and infra-red afterglow—the kilonova [9, 10], which was observed clearly in the aftermath of GW170817 [5]. This afterglow is likely driven by at least two components [11–13]: a “blue” kilonova driven by polar outflow [14] and a “red” kilonova driven by equatorial outflow [15]. These distinct components are believed to arise due to the different compositions of these outflows [11–13]. Relatively neutron rich outflows with an electron fraction \( Y_e \lesssim 0.275 \) can produce lanthanides [16], which are opaque to blue light [17, 18]. Less neutron-rich outflows (\( Y_e \gtrsim 0.275 \)) will produce nucleosynthetic yields which allow blue light to escape the photosphere [18, 19].

Several mechanisms can produce these outflows [20, 21]. Tidal ejection typically produces a blue component, while shock-driven, near-polar dynamical ejecta can potentially be blue [22–26]. Wind off of a remnant hypermassive, supramassive, or stable neutron star can also be blue [27]. However, a remnant-disk system can drive a wind [19, 22, 27–49]. For this last source, the composition is as-yet uncertain. Some studies show the disk wind to have an electron fraction ranging from \( Y_e \sim 0.2 \) – 0.4 and thus produce a blue component [38–41, 48, 49]. Other, recent work shows the disk wind to be uniformly composed of \( Y_e \sim 0.2 \) material that produces only a red component [44, 47].

We focus on the evolution of the post-merger disk. Until now, studies of the remnant disk wind have employed various approximations to the neutrino transport, neutrino-matter coupling, or magnetohydrodynamics (MHD). In this work, we present fully three-dimensional general-relativistic radiation magnetohydrodynamics (GRRMHD) simulations of a post-merger disk system with full neutrino transport using a Monte Carlo method.

We model a black hole accretion disk system which may have formed from the GW170817 merger [50]. Magnetohydrodynamic turbulence [51] drives a wind [52] off the disk. We find the electron fraction of this outflow ranges from \( Y_e \sim 0.2 \) to \( Y_e \sim 0.4 \). Moreover, we find that the composition of the outflow varies significantly with angle off of the midplane, suggesting that the observed character of the outflow depends heavily on viewing angle. Thus, a blue, wind-produced kilonova will be visible if the remnant is viewed close to the polar axis.

Methods—We perform a GRRMHD simulation in full three dimensions with our code, \( \nu bh light \) [54]. We assume a Kerr background metric, consistent with the relatively small disk mass compared to black hole mass. The radiation transport is treated via explicit Monte Carlo and the MHD is treated via finite volumes with constrained transport. The two methods are coupled via operator splitting.

We use the SFHo equation of state [55] as tabulated in [56, 57] and the neutrino-matter interactions described in [54] and tabulated in [58]. For initial data, we use parameters consistent with a remnant from GW170817 [1, 50, 59]: an equilibrium torus [60] of mass \( M_d = 0.12 \)
and constant electron fraction $Y_e = 0.1$ around a black hole of mass $M_{BH} = 2.58 \, M_\odot$ and dimensionless spin $a = 0.69$. We thread our torus with a single poloidal magnetic field loop such that the minimum ratio of gas to magnetic pressure is 100.

**Outflow Properties**—Our disk drives a wind consistent with other GRMHD simulations of post-merger disks [38–41, 44, 47–49], which expands outward from the disk in polar lobes. We record material crossing a sphere of radius $r \sim 10^3$ km. Figure 1 bins outflow material in both electron fraction $Y_e$ and in angle off the equator, $|90^\circ - \theta_{bl}|$ for Boyer-Lindquist angle $\theta_{bl}$, integrated in time. The 90% confidence interval for the viewing angle for GW170817 [53] is bounded by the dashed lines. We use the nuclear reaction network SkyNet [62] to compute nucleosynthetic yields on tracer particles advected with gravitationally unbound material. We start the network calculation when the tracer reaches $T \sim 10$ GK and we assume a nuclear statistical equilibrium (NSE) composition at that time. The network is run up to $t = 10^9$ s assuming homologous expansion ($\rho \propto t^{-3}$) and uses the same nuclear physics inputs as in [45, 63], namely: 8000 nuclides and 140,000 nuclear

$\frac{k_b}{\text{baryon}}$ and an average radial velocity (as measured at a radius of 1000 km) of about 0.1$c$.

The electron fraction depends on angle off of the midplane and this dependence persists through time. The right panel of figure 2 shows the average electron fraction of gravitationally unbound material passing through a surface at $t = 10^3$ km as a function of angle off the equator and time. For any given time, larger $|90^\circ - \theta_{bl}|$ correlates with larger $Y_e$.

We choose two regions, one close to the midplane, and one far from it, highlighted in the red and blue rectangles. We bin the electron fraction in these regions in the red and blue histograms. Regardless of electron fraction, ejected material has an average entropy, $s$, of about 20
Optical depth $\tau$ of neutrino absorption is the neutrino absorption distance. $\tau_e$ is the expected range of viewing angles for GW170817. The electron fraction of the outflow is calculated from the simulation. About 18% of this outflow has an electron fraction of $Y_e = 10^{-3}$, consistent with our results. For the latter, we assume an outflow mass of $M_{\text{out}} = 2 \times 10^{-2} M_\odot$, consistent with [47]. We use a mean radial velocity of $0.1c$.

Neutrino Transport — A characterization of the importance of neutrino absorption is the neutrino absorption optical depth $\tau$ of the disk. $\tau \ll 1$ implies free-streaming and $\tau \gg 1$ implies no neutrino can escape. At relatively early times ($t \lesssim 30$ ms), we find $\tau \sim 10$. In this phase, $Y_e$ evolution is dominated by escape of electron neutrinos in the core of the disk and their absorption in the corona. At later times ($t \gtrsim 30$ ms), the disk achieves a quasistationary state with $\tau \sim 0.1$. Although this later stage is emission dominated, reaching it requires properly treating absorption.

Outflow Mass — The left panel of figure 2 shows the total mass in the outflow as a function of time. Due to computational cost, we did not run our simulation for long enough to observe the total amount of mass that becomes gravitationally unbound. As a lower bound, we report the amount of material with Bernoulli parameter $B_c > 0$ [72] at a radius greater than 125 gravitational radii ($\sim 500$ km) at the end of the simulation ($\sim 127$ ms). (This includes material that has already left the domain.) We find this to be about $4.33 \times 10^{-3} M_\odot$ and the ratio of mass in the outflow accreted mass is about 9% by this time in the simulation. About 18% of this outflow has an electron fraction of $Y_e \geq 0.275$ and about 14.5% is within the expected range of viewing angles for GW170817.

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Elastic Optical Cut-off — The left panel of figure 2 shows the total mass in the outflow as a function of time. Due to computational cost, we did not run our simulation for long enough to observe the total amount of mass that becomes gravitationally unbound. As a lower bound, we report the amount of material with Bernoulli parameter $B_c > 0$ [72] at a radius greater than 125 gravitational radii ($\sim 500$ km) at the end of the simulation ($\sim 127$ ms). (This includes material that has already left the domain.) We find this to be about $4.33 \times 10^{-3} M_\odot$ and the ratio of mass in the outflow accreted mass is about 9% by this time in the simulation. About 18% of this outflow has an electron fraction of $Y_e \geq 0.275$ and about 14.5% is within the expected range of viewing angles for GW170817.

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FIG. 6: Electromagnetic spectra for spherically symmetric outflow composed of nucleosynthetic yields produced in material $<15^\circ$ off the midplane, $>50^\circ$ degrees off the midplane, and of solar abundances such as those produced in tidal ejecta or outflows like those reported in [47]. At 5000Å, the polar outflow is $\sim 12 \times$ more luminous than the more neutron-rich outflows.

Electromagnetic spectra indicate a blue kilonova, as viewed off the midplane. At 4000Å, the polar outflow is $\sim 15 \times$ more luminous than the red kilonova from tidal ejecta. The blue kilonova is consistent with other potential sources for a blue component and the red kilonova from tidal ejecta suggests a three (or more) component kilonova model, such as the one described in [81].

In a black hole-neutron star merger, only the tidal ejecta and accretion disk are present. An important observational implication of our model is that this disk-wind system is sufficient to produce a blue kilonova. This is in contrast to [44, 47], which would imply that black hole-neutron star mergers only produce a red kilonova.

Another important implication of our model is that accurately capturing the early transient phase of the disk, when optical depths are relatively large, is critical to correctly predicting the long-term outflow. Unfortunately, initial conditions are a source of uncertainty in kilonova disk modeling. A hot hypermassive or supramassive neutron star can emit its own neutrino flux, which can reset the electron fraction of the disk. Even in the absence of a hot remnant, the seed magnetic field is uncertain in both strength and topology. As the community moves forward more attention should be paid to both the initial transient phase of the disk and the initial conditions that drive this early phase.

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