Characterizing the evolution of the neutron star merger kilonova lightcurve with the James Webb Space Telescope

Abstract

The merger of a binary neutron star system (BNS) is an energetic and cataclysmic event that produces gravitational waves and an electromagnetic counterpart signal over a wide range of frequencies. In particular the radioactive decay of neutron rich heavy elements produced and ejected in the merger powers a transient signal in the ultraviolet to infrared regime, known as a kilonova. This kilonova was first jointly detected alongside the gravitational wave signal from a BNS merger in 2017, confirming the basic picture of the presence of heavy elements that radioactively decay over a few months. However, with only one sample measurement, many questions remain about the detailed nature of the kilonova composition. In particular, late time evolution on the order of a few days to few tens of days emits most dominantly in the infrared regime, and the evolution and exact shape of the light curve is determined by the radioactive elemental abundances in the ejecta. But as the source fades, beyond a few days the infrared light becomes too faint and difficult to detect. The recently launched James Webb Space Telescope has the sensitivity and accuracy to make such faint observations now possible in the infrared, and we propose to observe the long term evolution of the kilonova light curve with JWST when the next BNS merger event happens. This will allow us to constrain not only the dynamical properties of the merger and ejecta models more precisely, but also provide insight into the fraction of heavy elements we observe that are produced in such mergers.

Scientific Justification

In 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) made the first direct detection of gravitational waves from the rapid inspiral and merger of two black holes roughly thirty times more massive than our Sun [1]. This discovery heralded in a new era in astronomy, where we are now able to observe phenomena in the universe not just through the electromagnetic waves that they emit, but also through their gravitational wave signature.

Since that first detection, LIGO, along with the addition of two other detectors in Europe (Virgo) and Japan (KAGRA), have detected the gravitational waves from a confirmed 90 events involving the mergers of massive objects such as black holes and neutron stars [2]. The vast majority of these detected events come from the merger of two black holes, which is not expected to produce any electromagnetic signal. The rarer cases have been those that involve the merger of a neutron star with a black hole - which theoretically may or may not produce an electromagnetic signal depending on how massive the black hole is - or the merger of two neutron stars - which produces a counterpart electromagnetic signal across a wide range of frequencies known as a kilonova.

In order to exploit this newly available avenue of simultaneously observing events with gravitational waves and electromagnetic waves, we then need to focus on detecting merger events that involve two neutron stars. Indeed, the first (and so far only) simultaneous detection came in 2017 from the merger of two neutron stars, called GW170817 [3], and its transient counterpart AT2017gfo [4]. This multi-messenger event gave us a wealth of information, in particular the kilonova observed across the UVOIR spectrum yielded insights into heavy element nucleosynthesis [4].

This kilonova is powered by the radioactive decay of unstable neutron rich nuclei that are ejected in the merger event and undergo rapid neutron capture r-process nucleosynthesis. This

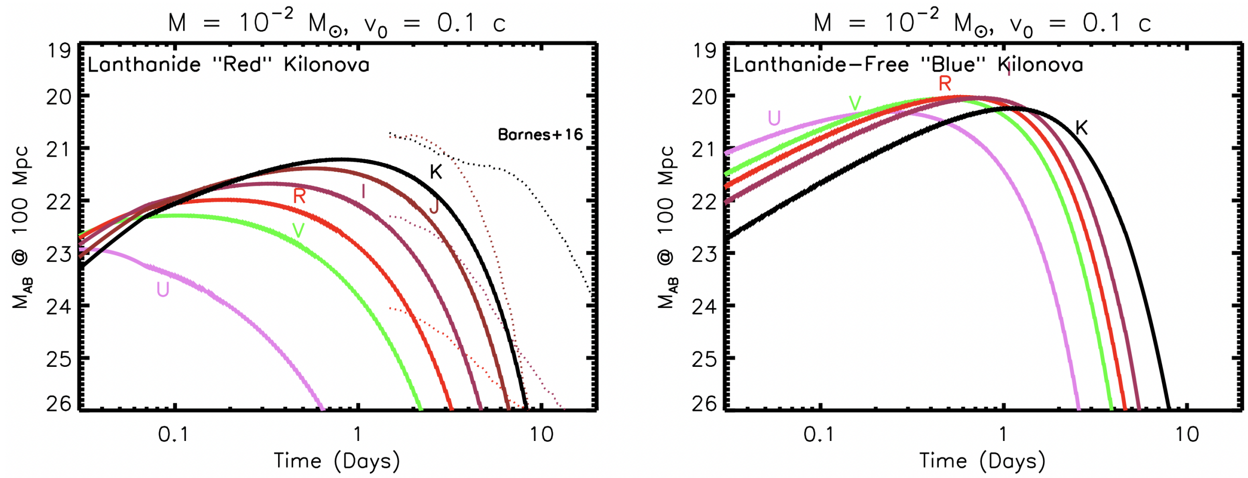

Figure 1: Kilonova light curves from an analytical model, showing how the fraction of blue and red components of the ejecta change the expected luminosity curves. In either case the emission peaks in the IR a few days after the merger. Figure from [5].

produces rare heavy elements in our universe such as gold and platinum [5]. The kilonova light-curve in the infrared part of the spectrum is particularly suited to multiple follow-up observations on the order of a few days to tens of days post-merger, as the emission does not fade as quickly as in the optical. This has to do with the different composition of the ejecta material and how it evolves differently over timescales. Lanthanide rich ejected material mainly emits in the infrared over longer timescales, while lanthanide-free components peak in the UV and optical [5].

From analytic models we have that the light curve is expected to have a peak in luminosity at

$$L_{peak} \approx 10^41\ ergs^{-1}(\epsilon_{th}/0.5)(M_{ej}/10^{-2}M_{\odot})^{0.35}(v/0.1c)^{0.65}(\kappa/1\ cm^2g^{-1})^{-0.65}$$

where ϵ_{th} is a thermalization efficiency parameter, M_{ej} is the ejecta mass, v is the ejecta velocity, and κ is the opacity [5]. The thermal efficiency parameter, and the opacity in particular is determined by the abundances of various heavy element radioactive isotopes, and so these two parameters tell us about the composition of the ejecta. We also have that at later times the specific heating rate (and thus the luminosity) follows a power law decrease as

$$\dot{e}_r \approx 2 \times 10^{10}\epsilon_{th}(t/1\ day)^{-1.3}\ ergs^{-1}g^{-1}$$

Fig. 1 shows an example of such a analytic model in which the fraction of lanthanide rich and lanthanide free elements is varied, and we can see how it shifts the observed light curve.

The recently launched James Webb space telescope (JWST) is designed to provide extremely sensitive observations in this infrared regime, and so is one of the best options to study kilonovae with. **With observations of the infrared light curve over many tens of days with JWST, we will be able to fit our model to the light curve and determine the ejecta mass, velocity and composition following a BNS merger.**

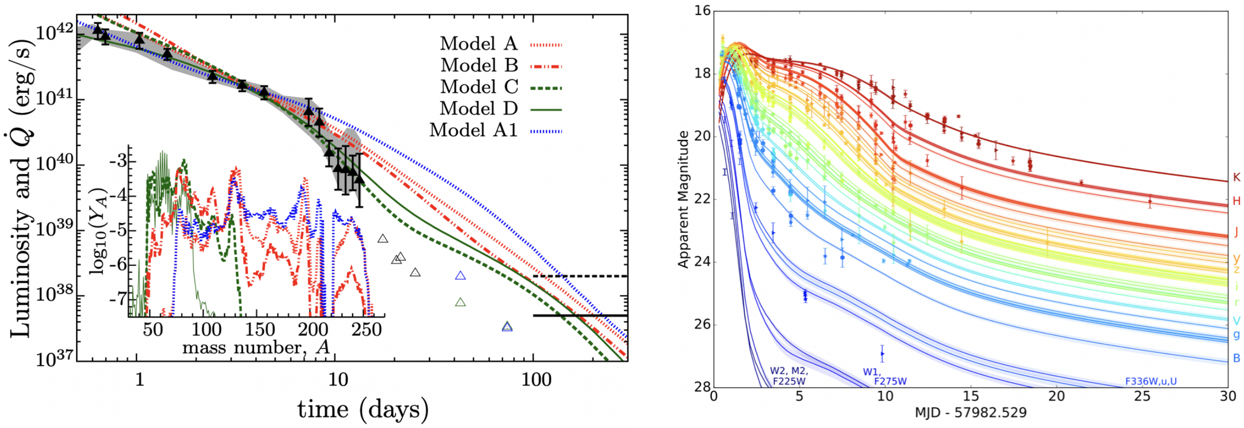

Figure 2: *Left* : Kilonova light curves for GW170817 and a range of models that could explain these observations. The colored lines show the ejecta heating rates for models with different values of the ejecta mass M_{ej} and average electron fraction Y_e. Note that we need more sensitive observations at both early and later times to constrain the models, that will be possible with JWST. Figure from [6]. *Right* : the multiband observations of the kilonova following GW170817 in the optical and infrared. We use these observed fluxes to scale to our JWST observations. Figure from [7].

Technical Justification

We request multi-epoch observations of the kilonova, with the first measurement at 3 days post-merger, followed by observations at 6 days and 10 days post-merger, and then request a set of long term observations at 20, 40 and 80 days post-merger. These observations are requested using the NIRCam (Near Infrared Camera) imaging instrument and the MIRI (Mid Infrared Instrument) in imaging mode.

Thus the first set of observations will study the evolution of the kilonova in the optically thick phase, and the next in the optically thin phase. As the infrared luminosity is expected to peak during the optically thick phase and lasts ~ 10 days [6], we measure this early evolution at the three different epochs characterizing the start, middle and end of this phase. For the optically thin phase we want to have observations spread over the time period where we expect the model varies the most, and we can thus most sensitively distinguish between the ejecta mass and composition of the emission. We can see in Fig. 2 (left) that this is between $\sim 10 - 100$ days. This upper limit is also determined by JWST's sensitivity, as the infrared flux falls below JWST detection sensitivity (within a reasonable 10 ksec exposure time) of $m \sim 29$ beyond ~ 100 days. We cover this range again with three measurements near the start, middle and end of this window (20, 40, 80 days post merger).

It is the sensitivity of the JWST imaging instruments to point sources as faint as $m \approx 29$ in the infrared regime that uniquely positions it to be able to perform these observations of the kilonova light curve in the late time optically thin phase, which no other telescope can currently perform, and give us exquisite accuracy for the measurements in the early optically thick phase.

For the measurements we propose we require one of the lowest wavelength filters available, which is the F090W, centered at a wavelength of 0.9 μm. Since NIRCam uses a dichroic to simultaneously observe in one short wavelength channel ($0.6 - 2.3$ μm) and one long wavelength channel ($2.4 - 5.0$ μm), we will also observe with the F444W, centered at a wavelength of 4.44 μm, which is one of the longest wavelength filters on the NIRCam instrument. These filters are furthermore chosen as they have a wide bandwidth and thus cover a larger spectral range, which helps constrain the estimate for the bolometric luminosity. For the MIRI instrument we request use of the wide F770 (7.7 μm) filter.

To measure the exposure time we first estimate the expected flux we might expect from a kilonova. To do this we consider the observed flux m_{17} in the various bands from AT2017gfo (Fig. 2, which we know was at a distance of 40 Mpc), and scale them to a nominal distance of ~ 150 Mpc, which is the predicted median detection distance by LVK for BNS mergers in O4 [8]. We calculate the magnitudes as $m = m_{17} + 5log_{10}(150/40) \approx m_{17} + 3.0$. Thus for example while AT2017gfo had an apparent magnitude of 18 in the z-band (centered at 0.9 μm, same as the NIRCam F090W filter we propose to use), we calculate the exposure time based on an expected flux of magnitude $m = 21$ in this filter.

In the JWST online exposure time calculator we set our background sky location to that of AT2017gfo for the purposes of estimating a background noise, and set the background noise configuration to 'medium' (50th percentile) for that area of the sky. We then vary the exposure time until we get a signal-to-noise ratio of 10 for each exposure in each observing filter. Thus our requested times for the 6 observing epochs (3, 6, 10, 20, 40, 80 days post-merger), are: i) for NIRCam: 50 s, 110 s, 450 s, 1030 s, 1890 s, 4120 s, and ii) for MIRI: 80 s, 250 s, 790 s, 1780 s, 4880 s, 7550 s. **In total we request 6.4 hours of science observation time with JWST.**

It is also important to note that this is a target of opportunity event that will be triggered only when a detection of a BNS merger and its optical counterpart is made. Using the rate of BNS mergers detected so far, the LVK collaboration predicts that with the updated sensitivities of the Advanced detectors during the fourth observing run (O4, BNS range 160-190 Mpc), that the number of BNS events detected in one year of duty cycle given will be 10^{+52}_{-10} [8]. If all 4 detectors are observing, then the LVK estimates that the median sky localization accuracy will be 33^{+5}_{-5} deg^2 [8]. For comparison, for the GW170817 event detected during O2, the rapid sky localization was 31 deg^2 at the 90% credible area [4]. This is too large a patch of sky for JWST to observe, which has a field of view of 9.7 $arcmin^2$ with the NIRCam, and an even smaller 2.3 $arcmin^2$ with MIRI. Fortunately there exist many ground based survey telescopes with large fields of view and sufficient depth that can detect the early optical emission of some of these kilonovae to determine the host galaxy and pinpoint its location within $\sim 1 - 2$ days. Indeed, detailed simulation work shows that the Zwicky Transient Facility telescope is expected to be able to rapidly detect ~ 5 kilonovae in O4, and the Large Synoptic Survey Telescope ~ 3 [9]. Thus we will trigger our JWST observations only once one of these ground based telescopes has made a detection.

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