The Combined Ultraviolet, Optical, and Near-infrared Light Curves of the Kilonova Associated with the Binary Neutron Star Merger GW170817: Unified Data Set, Analytic Models, and Physical Implications

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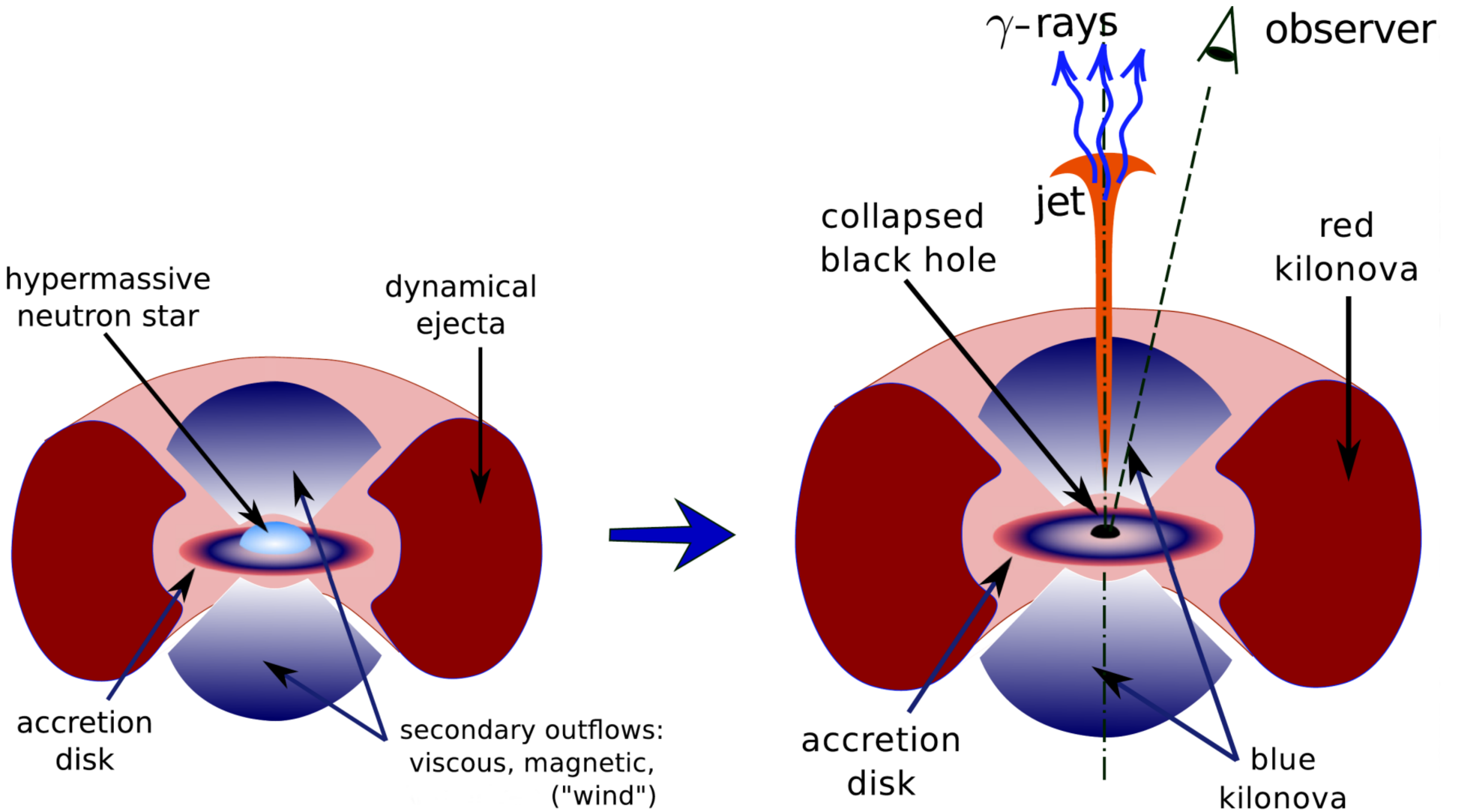
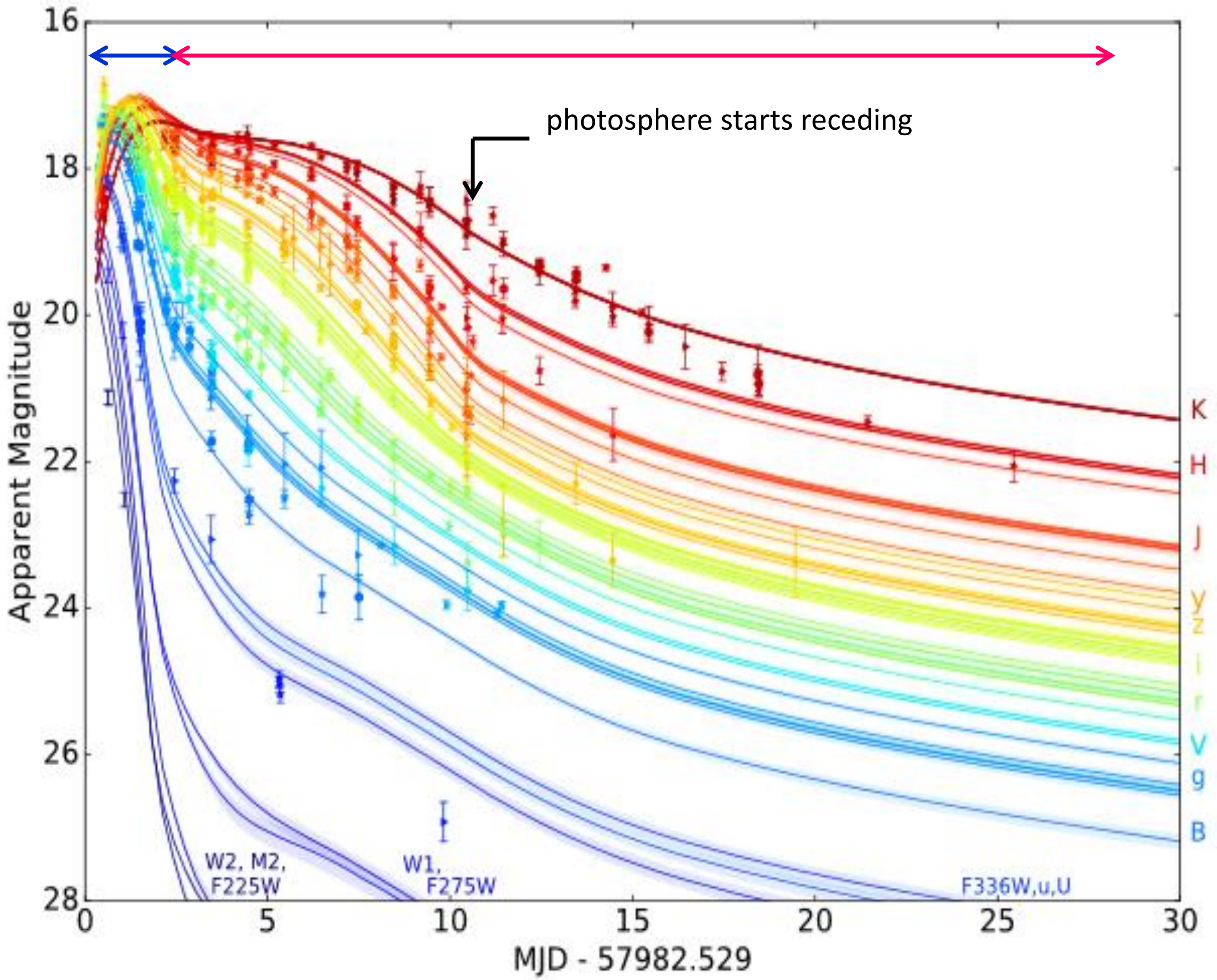
Abstract

We present the first effort to aggregate, homogenize, and uniformly model the combined ultraviolet, optical, and near-infrared data set for the electromagnetic counterpart of the binary neutron star merger GW170817. By assembling all of the available data from 18 different papers and 46 different instruments, we are able to identify and mitigate systematic offsets between individual data sets and to identify clear outlying measurements, with the resulting pruned and adjusted data set offering an opportunity to expand the study of the kilonova. The unified data set includes 647 individual flux measurements, spanning 0.45–29.4 days post-merger, and thus has greater constraining power for physical models than any single data set. We test a number of semi-analytical models and find that the data are well modeled with a three-component kilonova model: a "blue" lanthanide-poor component ($\kappa = 0.5\,\mathrm{cm^2\,g^{-1}}$) with $M_{\rm ej} \approx 0.020\,M_\odot$ and $v_{\rm ej} \approx 0.27c$; an intermediate opacity "purple" component ($\kappa = 3\,\mathrm{cm^2\,g^{-1}}$) with $M_{\rm ej} \approx 0.047\,M_\odot$ and $v_{\rm ej} \approx 0.15c$; and a "red" lanthanide-rich component ($\kappa = 10\,\mathrm{cm^2\,g^{-1}}$) with $M_{\rm ej} \approx 0.011\,M_\odot$ and $v_{\rm ej} \approx 0.14c$. We further explore the possibility of ejecta asymmetry and its impact on the estimated parameters. From the inferred parameters we draw conclusions about the physical mechanisms responsible for the various ejecta components, the properties of the neutron stars, and, combined with an up-to-date merger rate, the implications for *r*-process enrichment via this channel. To facilitate future studies of this keystone event we make the unified data set and our modeling code public.

General picture



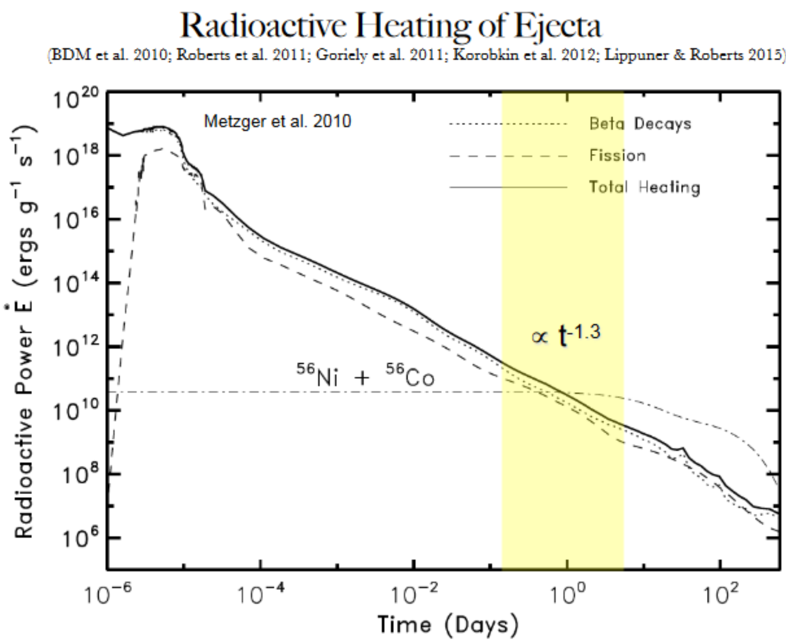
2. Ultraviolet, Optical, and Near-infrared Data



3. Kilonova model

Ingredients:

- Radioactive heating: β decay of an assembly of neutron-rich nuclei



$L_{in}(t) \propto t^{-\alpha}$ with $\alpha \sim 1.3$

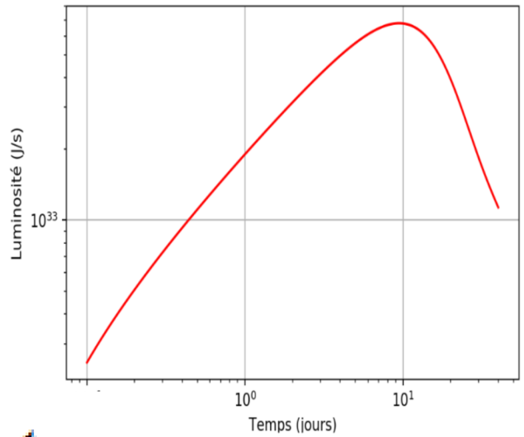
- Heating efficiency: $\varepsilon_{th}(t)$: 10-30% at 10 days, a few percent at one month
- Diffusion time scale in the expanding envelope

$$\tau_d \sim \frac{R^2}{\lambda c} \sim \frac{\kappa \rho R^2}{c} \sim \frac{\kappa M}{Rc} \sim \frac{\kappa M}{v_{exp} c\, t} = \frac{t_d^2}{2t} \quad \text{with } t_d = \left(\frac{2\kappa M}{v_{exp} c}\right)^{1/2}$$

$\lambda = (\kappa \varrho)^{-1}$ mean free path ; free expansion: $R = v_{exp} t$

Thermal equation for the expanding envelope (simplified):

$$\frac{dL_{bol}}{dt} = \frac{1}{\tau_d}\left[-L_{bol} + L_{in}\varepsilon_{th}\right] \text{ with } \quad \tau_d = \frac{t_d^2}{2t}$$



leads to

$$L_{\rm bol}(t) = \exp\left(\frac{-t^2}{t_d^2}\right) \times \int_0^t L_{\rm in}(t)\,\epsilon_{\rm th}(t) \exp\left(t^2/t_d^2\right) \frac{t}{t_d}\, d(t/t_d) \qquad (3)$$

→ luminosity from radioactivity convolved with diffusion in the expanding envelope

From the bolometric luminosity to the luminosity in a spectral band:

→ blackbody spectrum assumed at temperature:

$$T_{phot}(t) = \max\left[\left(\frac{L_{bol}(t)}{4\pi\sigma v_{exp}^2 t^2}\right)^{1/4}, T_c\right] \qquad (4)$$

$$R_{phot}(t) = v_{exp}t \quad (T_{phot} > T_c) \quad ; \quad R_{phot}(t) = \left(\frac{L_{bol}(t)}{4\pi\sigma T_c^4}\right)^{1/2} \quad (T_{phot} = T_c)$$

→ photosphere recedes in lagrangian coordinates

4. Results of the kilonova models

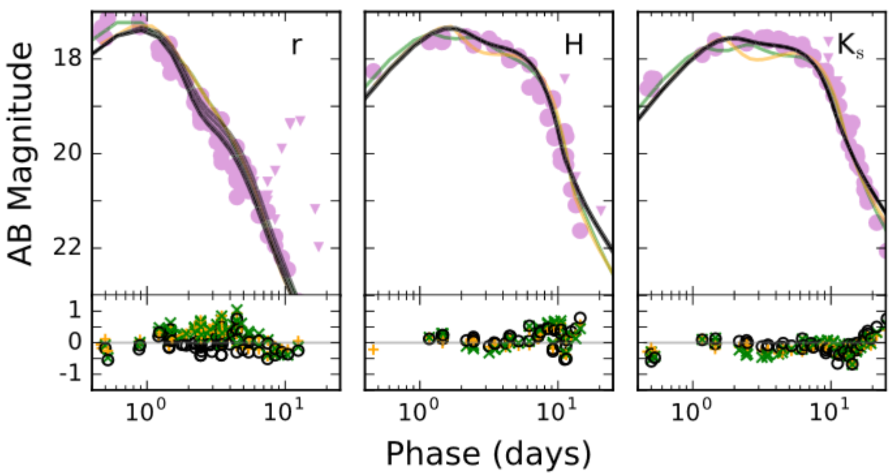
Fitting the multi-wavelength data to find M , v_{exp} , (κ) , T_c

→ no single component solution: best solution with a three component model

Table 2
Kilonova Model Fits

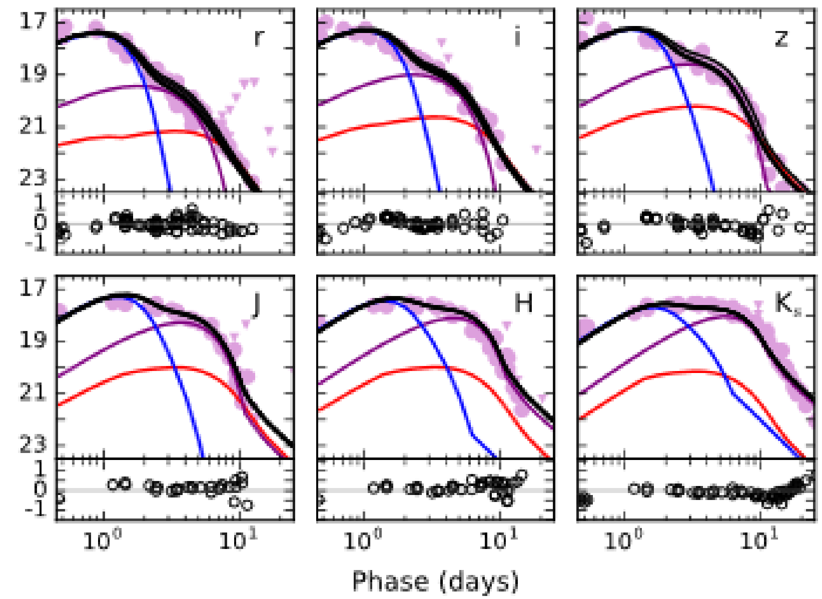
Model	M_{ej}^{blue}	v_{ej}^{blue}	κ_{ej}^{blue}	T^{blue}	M_{ej}^{purple}	v_{ej}^{purple}	κ_{ej}^{purple}	T^{purple}	M_{ej}^{red}	v_{ej}^{red}	κ_{ej}^{red}	T^{red}
2-Comp	$0.023^{0.005}_{0.001}$	$0.256^{0.005}_{0.002}$	(0.5)	3983^{66}_{70}	···	···	···	···	$0.050^{0.001}_{0.001}$	$0.149^{0.001}_{0.002}$	$3.65^{0.09}_{0.28}$	1151^{45}_{72}
3-Comp	$0.020^{0.001}_{0.001}$	$0.266^{0.008}_{0.008}$	(0.5)	674^{486}_{417}	$0.047^{0.001}_{0.002}$	$0.152^{0.005}_{0.005}$	(3)	1308^{42}_{34}	$0.011^{0.002}_{0.001}$	$0.137^{0.025}_{0.021}$	(10)	3745^{75}_{75}
Asym. 3-Comp	$0.009^{0.001}_{0.001}$	$0.256^{0.009}_{0.004}$	(0.5)	3259^{302}_{306}	$0.007^{0.001}_{0.001}$	$0.103^{0.007}_{0.004}$	(3)	3728^{94}_{178}	$0.026^{0.004}_{0.002}$	$0.175^{0.011}_{0.008}$	(10)	1091^{29}_{45}

Fig.5



Black: 3-Comp
Orange: 2-Comp
Green: Asym. 3-Comp

Fig.4



Fits with the 3-Component model

Also results for the color evolution (Fig.3)

5. Discussion and implications

- 3-component (spherical) model fits the data well:
  M: 0.078 $M_\odot$ (0.02 + 0.047 + 0.011) ; v/c: (0.266 – 0. 152 – 0.137)
- blue ejecta: proton-rich, mostly polar, from a short-lived neutron star
- red/purple ejecta: tidal tails (during coalescence)/outflow from the disk
- asymmetric models (should be preferred) : smaller ejected mass 0.042$M_\odot$
- ejected masses consistent r-process elements being formed in mergers

merger rate: 1500 Gpc^{-3} yr^{-1} ; density of MW-like galaxies: 10^7 Gpc^{-3}
$\rightarrow$ merger rate/galaxy: 1. 5 10^{-4} yr^{-1}

estimated production rate of r-process elements : a few 10^{-7} $M_\odot$ yr^{-1}/galaxy
$\rightarrow$ requires a few 10^{-3} $M_\odot$ of r-process elements/merger
compatible with the results for the kilonova in the August 17 event.

6. Conclusions

1. We present 647 photometric measurements from the kilonova accompanying the binary neutron star merger GW170817, spanning from 0.45 to 29.4 days post-merger and providing nearly complete color coverage at all times. We make the homogenized data set available to the public in Table 3, in the OKC, and through https://kilonova.org/.
2. The kilonova UVOIR light curves are well fit by a spherically symmetric, three-component model with an overall ejecta mass of $\approx 0.078\,M_{\odot}$, dominated by light *r*-process material ($A < 140$) with moderate velocities of $\approx 0.15c$.
3. We find evidence for a lanthanide-free component with mass and velocity of $\approx 0.020\,M_{\odot}$ and $\approx 0.27c$, respectively. This component is indicative of polar dynamical ejecta, and hence a BNS origin (instead of NS–BH). The large ejecta mass implies a small neutron star radius of $\lesssim 12$ km.
4. The mass and velocities of the purple/red components are consistent with a delayed outflow from an accretion disk formed in the merger. This disfavors a long-lived ($\gtrsim 100$ ms) hyper-massive neutron star remnant and provides evidence for relatively prompt formation of a black hole remnant.
5. The asymmetric model extension implies that the total ejecta mass may be up to a factor of 2 times lower than for the symmetric model.
6. Given the large uncertainties in BNS merger rates, we find that the *r*-process production rates are comfortably above the Galactic production rate, consistent with the idea that BNS mergers are the dominant source of *r*-process nucleosynthesis in the universe.