Prospects of Gravitational-wave Follow-up through a Wide-field Ultraviolet Satellite: A Dorado Case Study

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Abstract

The detection of gravitational waves from the binary neutron star merger GW170817 and electromagnetic counterparts GRB170817A and AT2017gfo kick-started the field of gravitational-wave multimessenger astronomy. The optically red to near-infrared emission (“red” component) of AT2017gfo was readily explained as produced by the decay of newly created nuclei produced by rapid neutron capture (a kilonova). However, the ultraviolet to optically blue emission (“blue” component) that was dominant at early times (up to 1.5 days) received no consensus regarding its driving physics. Among many explanations, two leading contenders are kilonova and ultraviolet satellite models. While the same ultraviolet data and optical data starting at 12 hr have limited ability to constrain model parameters separately, the combination of the two unlocks tight constraints for all but one parameter of the kilonova model up to 160 Mpc. We further find that a Dorado-like ultraviolet satellite can distinguish the early radioactivity models up to at least 130 (60) Mpc if data collection starts within 3.2 (5.2) hr for AT2017gfo-like light curves.

Unified Astronomy Thesaurus concepts: Bayesian statistics (1900); Gravitational waves (678); Model selection (1912); Neutron stars (1108); Nucleosynthesis (1131); Ultraviolet astronomy (1736)

1. Introduction

The LIGO-Virgo collaboration can now regularly detect and study gravitational waves (GWs) from the final moments of inspiraling compact object mergers (Abbott et al. 2020). At least some compact binary mergers involving a neutron star (NS) are expected to produce electromagnetic (EM) counterparts, depending on mass-ratio and spins (for a review, see, e.g., Nakar 2020). The discovery of a binary neutron star (BNS) merger GW170817 (Abbott et al. 2017a) and subsequent EM counterparts, the γ-ray burst (GRB) GRB170817A (Goldstein et al. 2017; Savchenko et al. 2017) and ultraviolet, optical, and infrared (UVOIR) counterpart AT2017gfo (e.g., Abbott et al. 2017b, 2017c; Arcavi et al. 2017; Chornock et al. 2017; Coulter et al. 2017; Kasliwal et al. 2017; Lipunov et al. 2017; Shappee et al. 2017; Soares-Santos et al. 2017; Valenti et al. 2017), kick-started the era of GW multimessenger astronomy. AT2017gfo exhibited a featureless thermal spectrum, peaking in the near ultraviolet (UV) at ~1 day (“blue” component). After this time the blue component faded while
long-lived NS central remnant (e.g., Shibata et al. 2017; Metzger et al. 2018; Nedora et al. 2021), but in the case of AT2017gfo such winds would have difficulties explaining the high velocities inferred for the early emission. Still, Waxman et al. (2018) found that a single ejecta component kilonova model, but with a uniform time dependent opacity ($\kappa \propto t$), is consistent with the available data. Alternatively, other model ingredients may be driving the blue component, such as a precursor powered by free neutron decay (Metzger et al. 2015; Gottlieb & Loeb 2020) or shock interaction, also known as cocoon emission (Kasliwal et al. 2017; Piro & Kollmeier 2018).

One critical aspect that was missing in the observations of AT2017gfo was UV data in the first hours. Swift/UVOT obtained their first exposure in the UV band ($\sim$200–300 nm) at $\Delta t = 0.6$ days (15 hr) after the GW trigger (Evans et al. 2017) of GW170817. Early UV data would provide the essential diagnostic to identify the main mechanism or combination of mechanisms that power the UV and optically blue radiation in the first few hours (Arcavi 2018).

One way to obtain such data would be by having a large field-of-view (FOV) UV satellite on standby to rapidly follow up on GW triggers to find the target in the GW localization sky area while it is still bright in UV in the first few hours. In this work we first consider the performance of the Dorado mission concept (Singer et al. 2021) for such prompt GW follow-up in the UV. Dorado consists of a SmallSat (slightly larger than a 12U CubeSat) spacecraft equipped with a 13 cm refractive (7 element) telescope with a 50 deg$^2$ FOV. The instrument adopts a single (fixed) bandpass over the wavelength range from 185 to 215 nm. The Dorado camera employs delta-doped charge coupled device detectors to provide surface passivation and reflection-limited response over the UV bandpass (Nikzad et al. 2017).

Dorado underwent a Phase A Concept Study in 2020–2021 but was not selected for implementation by NASA. While differing in some implementation details, several other mission concepts in development also propose similar GW follow-up science objectives. The most similar concepts to Dorado include ULTRASAT (Sagiv et al. 2014)—a 200 deg$^2$ single-band near-UV imager led by Israel and scheduled for launch in 2025—and UVEX (Kulkarni et al. 2021)—a 12 deg$^2$ dual-band (near- and far-UV) imager and spectrograph currently undergoing a Phase A Concept Study as a NASA Medium Explorer mission (potential launch date ~2028). Summary mission specifications of Dorado, ULTRASAT, and UVEX are given in Table 1, and we discuss the simulation of photometric data with Dorado in detail in Section 3.3. We also note that recently Chase et al. (2022) performed a kilonova detectability study for a wide range of wide-field instruments.

In this study, we perform a Bayesian analysis to examine to what degree satellite-based UV photometry could distinguish between two competing emission models for AT2017gfo-like blue emission. The two models considered are $r$-process nucleosynthesis (kilonova) and shock interaction (cocoon emission). Currently, these two options are prominent in the literature, and the data of AT2017gfo allow for either a pure shock interaction or kilonova scenario to explain the blue component. In addition, we study to what degree the data constrain parameters of either model. We also perform an analysis with ground-based optical and joint UV and optical (UVO) data to examine the added value of early UV photometry. Finally, we study how delayed observation affects model selection and parameter estimation for satellite-based UV.

This paper is structured as follows: Section 2 describes the kilonova and shock-interaction models. Section 3 describes the Bayesian theoretical framework and the simulation of light curves and photometric data. Section 4 presents the results of the Bayesian analysis. Section 5 presents our main findings and implications for planned UV missions, discusses caveats for this work, and concludes.

### 2. Radiation Models

This section provides a summary of the physics of the two radiation models and discusses the model parameters.

#### 2.1. Nucleosynthesis Powered Model

The first radiation model is the Hotokezaka & Nakar (2020) model for radiation powered by $\beta$-decay of radioactive elements produced through $r$-process nucleosynthesis (kilonova). This is a semianalytic model, based on the Arnett model (Arnett 1982). The latter models the light curves for supernovae and as such includes the radioactive decay of $^{56}$Ni and $^{56}$Co. Hotokezaka & Nakar (2020) apply the Arnett model to kilonovae, however, and solve the time evolution of $\beta$-decay chains for all elements up to a certain mass $A$ to get the radioactive power of each decay chain. For simulations performed here elements up to $A = 209$ are included. Here, we do not include the heating due to $\alpha$-decay and fission because their contributions are rather small in the early times, where kilonovae are expected to be bright in the UV. Thermalization is treated similarly to analytic methods presented by Kasen & Barnes (2019) and Waxman et al. (2019), with injection energies of each decay product specified per decay chain.

The model assumes isotropic geometry where the radial density structure of the ejecta is modeled as a function of time $t$ and velocity $v$, given by

$$\rho(t, v) = \rho_0(t) \left(\frac{v}{v_{\text{min}}}\right)^{-n} \quad (v_{\text{min}} \leq v \leq v_{\text{max}}),$$

where $\rho_0(t)$ ensures that the full $M_{\text{ej}}$ is retrieved when the density $\rho(t, v)$ is integrated over the full velocity range $[v_{\text{min}}, v_{\text{max}}]$. Parameter $n$ defines how steeply the power-law density distribution falls off. The ejecta are modeled here as finely discretized mass shells, and a notable feature is that radiative transfer is improved by accounting for radiation escape from mass shells with different expansion velocities in

| Mission       | 5σ (AB) (15 minute exp.) | Response Time | $\Omega$ (deg$^2$) | Orbit |
|---------------|--------------------------|---------------|------------------|-------|
| Dorado        | 20.8                     | ~30 minutes   | 50               | LEO   |
| ULTRASAT      | 22.3                     | ~30 minutes   | 200              | GEO   |
| UVEX          | 25                       | <3 hr         | 12               | HEO   |

Note. From left to right, the table presents the 5σ limiting magnitude (AB) for given exposure time, response time, FOV, and orbit type. LEO, GEO, and HEO are low-earth, geosynchronous, and high-earth orbit, respectively.
the case where the diffusion time is long compared to the dynamical time.

The opacity of the ejecta is modeled as two concentric piecewise opacity zones: an inner opacity $\kappa_{in}$ and outer opacity $\kappa_{out}$. The inner, transition, and outer borders of the opacity zones are defined by outward radial velocities $v_{\text{min}}, v_{\text{trans}},$ and $v_{\text{max}}$; Note that bound-bound transitions of heavy elements dominate the kilonova opacities, which in reality vary with the wavelengths and ejecta conditions, such as temperature and density (e.g., Banerjee et al. 2020; Tanaka et al. 2020). Here, however, we assume opacity to be constant with time and wavelengths for simplicity. An effective radius and temperature are calculated such that the model produces effective blackbody radiation. Our adaptation of the model is publicly available on GitHub.\(^{10}\)

2.2. Shock-interaction Powered Model

The second radiation model is an analytical shock-interaction model derived by Piro & Kollmeier (2018). It follows analytical work presented in Nakar & Piran (2017) and includes some added details to facilitate comparison with AT2017gfo. In this model, a relativistic GRB jet punches through ejecta material, depositing some of its energy to the ejecta and thereby inflating it to create a shock-heated cocoon. The light curve is powered by the cooling emission of this shock-heated material. Such a model could also represent a shock driven by a short-lived magnetar (Metzger et al. 2018). Similar to the kilonova model, this model contains no angular dependence and emits effective blackbody radiation.

The shock model assumes an initial shock radius $R$ corresponding to the radius of the ejecta at the time when the GRB first punches through. For GW170817, $R \sim 10^{10}-10^{11}$ cm, corresponding to a jet traveling at $\sim 1.7 \text{ s}$ to emerge, as derived from the delay time between GW170817 and GRB170817A (Abbott et al. 2017b; Goldstein et al. 2017; Savchenko et al. 2017). The shocked envelope is assumed to have energy distributed with respect to velocity as

$$\frac{dE}{dv} \propto v^{-s},$$

where it is assumed that $s > -1$. The parameter $s$ encodes ignorance on how exactly the jet deposits its energy in the ejecta. As in Piro & Kollmeier (2018), we assume $s = 3$, which is derived from AT2017gfo. The luminosity $L$, effective temperature $T_{\text{eff}}$, and effective radius $r_{\text{eff}}$ are given by

$$L = 9.5 \times 10^{40} \kappa_{0.1}^{-3/2} M_{0.01}^{2.5} M_{\text{day}}^{8/5} R_{0.01}^{-4/5} \text{ erg s}^{-1},$$

$$T_{\text{eff}} = 6.2 \times 10^{12} \kappa_{0.1}^{-7/3} M_{0.01}^{1/60} v_{0.1}^{1/15} R_{10}^{1/4} r_{\text{day}}^{8/15} \text{ K},$$

$$r_{\text{eff}} = 3 \times 10^{13} \kappa_{0.1}^{1/6} M_{0.01}^{2/5} \nu_{0.1}^{2/3} r_{\text{day}} \text{ cm},$$

where $M_{0.01}$ is the shocked mass in units of $0.01 M_\odot$, $\kappa_{0.1}$ is the opacity in units of $0.1 \text{ cm}^2 \text{ g}^{-1}$, $v_{0.1}$ is the minimum ejecta velocity in units of $0.1 c$, $R_{10}$ is the initial shock radius in units of $10^{10}$ cm, and $r_{\text{day}}$ denotes the days elapsed since the merger.

3. Methodology

We perform a Bayesian analysis to quantify the degree to which various photometric data distinguishes the radiation models and allows for parameter estimation. This section elaborates on our methodology and is structured as follows: Section 3.1 provides a short summary of the relevant theory of Bayesian model selection and parameter estimation. In this study, the input data for the Bayesian analysis is simulated in two steps. First, Section 3.2 defines “fiducial” (i.e., AT2017gfo-like) light curves computed with the models introduced in Section 2. Second, Section 3.3 lays out how an observation of these light curves is simulated, producing simulated photometric data.

3.1. Bayesian Framework

Bayesian model selection and parameter estimation (for an in-depth review, see, e.g., Sivia & Skilling 2006) rely on some data $D$ and a model $M$ described by a set of parameters $\theta$. The posterior probability is given by

$$P(\theta|D, M) = \frac{P(D|\theta, M) P(\theta|M)}{P(D|M)} = \frac{L(\theta) \pi(\theta)}{Z},$$

where $L(\theta) = P(D|\theta, M)$ is the likelihood function and $\pi(\theta) = P(\theta|M)$ is the prior. The evidence (marginal likelihood) $Z$ is given by

$$Z = P(D|M) = \int_{\Omega_\theta} L(\theta) \pi(\theta) d\theta,$$

with the integral taken over the whole domain $\Omega_\theta$ of $\theta$. For a given set of data $D$, we can quantify how it supports one model $M_A$ compared to another $M_B$ by the ratio of evidences. This is also known as the Bayes factor:

$$B_{AB} = \frac{P(M_A|D)}{P(M_B|D)} = \frac{Z_A}{Z_B}.\quad(8)$$

Using Bayes’ rule, we can relate the Bayes factor to the posterior ratio:

$$\frac{P(M_A|D)}{P(M_B|D)} = \frac{P(D|M_A)}{P(D|M_B)} \frac{P(M_A)}{P(M_B)} = B_{BA}^B P(M_A),$$

where $P(M_i), i = A, B$ is the prior probability of each model. Equation (9) shows that the posterior ratio is equivalent to the prior ratio “updated” by the Bayes factor because the Bayes factor is the term that contains all information regarding the new data. In other words, the Bayes factor quantifies the “distinguishability power” of a set of data. A value of $B_{AB} > 1$ means that $M_A$ is more strongly supported by the data under consideration than $M_B$, Kass & Raftery (1995) provide a guide for the interpretation of Bayes factors and judge that $B_{AB} > 100$ (or $\log_{10}(B_{AB}^B) > 2$) can be regarded as being “decisive.” We will assume this number as a threshold for confident model selection.

3.2. Fiducial Light Curves

There is no consensus in the early evolution of light curves of BNS mergers. While one EM counterpart of a BNS merger...
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Table 2
Various Parameters of the Three Fiducial Light Curves

| Parameter (Unit) | Description                                           | Prior Density                  | Fiducial Value |
|------------------|-------------------------------------------------------|--------------------------------|----------------|
| $M_{ej}$ ($M_\odot$) | Ejecta mass                                          | $U(0.001, 0.1)$                | 0.05           |
| $v_{\text{min}}$ ($c$)     | Minimum ejecta velocity                                | $U(0.005, 0.2)$                | 0.1            |
| $v_{\text{max}}$ ($c$)     | Maximum ejecta velocity                                | $U(0.3, 0.8)$ [$U(0.21, 0.8)$] | 0.4 [0.23]    |
| $k_{\text{ej}}$           | Power-law index of ejecta density distribution         | $U(3.5, 5)$                    | 4.5            |
| $v_{\text{transition}}$ ($c$) | Transition velocity between high and low $\kappa$  | $U(v_{\text{min}}, v_{\text{max}})$ | 0.2 [0.2] |
| $\kappa_{\text{high}}$ ($c^2$ g$^{-1}$)   | Effective gray opacity for $v \lesssim v_{\kappa}$ | $U(1, 10)$                     | 3              |
| $\kappa_{\text{low}}$ ($c^2$ g$^{-1}$)    | Effective gray opacity for $v \gtrsim v_{\kappa}$   | $U(0.1, 1)$ [$U(0.01, 0.1)$]  | 0.5 [0.04]    |

**Shock-interaction Powered Model**

| Parameter (Unit) | Description                                           | Prior Density                  | Fiducial Value |
|------------------|-------------------------------------------------------|--------------------------------|----------------|
| $M_{sh}$ ($M_\odot$) | Shocked ejecta mass                                   | $U(0.005, 0.05)$               | 0.01           |
| $v_{\text{sh}}$ ($c$)     | Shocked ejecta minimum velocity                       | $U(0.1, 0.3)$                  | 0.2            |
| $R_0$ ($10^{10}$ cm)     | Initial shock radius                                  | $U(1, 10)$                     | 5              |
| $\kappa_{\text{sh}}$ ($c^2$ g$^{-1}$) | Effective gray opacity of shocked ejecta | $U(0.1, 1)$ | 0.5            |

**Note.** The top half displays the parameters and prior distributions of the “default” and “lower early opacity” kilonova models, where differing values for the “lower early opacity” kilonova model are given in square brackets. The bottom half displays the same for the shock-interaction model. On the left-hand side, input parameters are given along with units in parentheses. The prior distributions, which are used in the Bayesian analysis, are given in the third column, where the $U$ (min, max) notation is used to indicate the minimum and maximum values of a uniform probability distribution. In the right-hand column, the fiducial values for the fiducial light curves are given.

![Figure 1](image-url)

**Figure 1.** Comparison of the three fiducial light curves in the Dorado UV band (185 to 215 nm) at luminosity distance $d_L = 40$ Mpc and including Milky Way dust extinction. The blue curve is the shock-interaction model, the orange curve is the “default” kilonova model, and the green curve is the “lower early opacity” kilonova model. The error bars on the curves correspond to $1\sigma$ errors for 10 minute exposures. For each light curve, there are 14 exposures observed with identical 97 minute cadence. For reference, the vertical dashed–dotted line indicates the timing of the first UV data recorded of AT2017gfo by Swift/UVOT at 15 hr (Evans et al. 2017).

The second fiducial light curve is called the “lower early opacity” light curve and is displayed as a green curve in Figure 1. Its inclusion here is motivated by recent work by Banerjee et al. (2020) who found light curves with early UV brightness that peak 1.5–2 mag brighter than the “default” model. Rather than using a (multiple-zone) gray opacity model, they performed a radiative transfer simulation using opacities calculated by taking into account atomic structures, including highly ionized light $r$-process elements ($Z = 20–56$). The “lower early opacity” light curve is a least-squares fit with our kilonova model in both their simulated peak brightness and real Swift/UVOT data from AT2017gfo in AB magnitude. For this fit, we only allowed $v_{\text{transition}}$, $v_{\text{max}}$, and $\kappa_{\text{low}}$ to vary, minimizing the change on the late-time light curve while allowing for a good fit with the early UV light curve of Banerjee et al. (2020). The resulting model parameters and prior distributions are shown in Table 2, but we find that $v_{\text{transition}}$ remains the same. We also note that the AB magnitude of the “lower early opacity” light curve at 0.1 day is brighter by $\sim 1$ mag than the “light $r$-process+Sm+Nd+Eu” model of Banerjee et al. (2022), where they perform a radiative transfer simulation accounting for the expansion opacities of highly ionized lanthanide elements. Third and lastly, we include a fiducial light curve produced using the shock-interaction model, which is given as a blue curve in Figure 1. This fiducial light curve corresponds to the fit of AT2017gfo by photometric data obtained from AT2017gfo.
Figure 2. Bayes factors obtained from satellite-based UV, optical r band, or joint UV+r data, under the base-case observation timing scenario. Left: resulting Bayes factors when distinguishing the shock-interaction model from “default” kilonova model. Right: distinguishing the shock-interaction model from the “lower early opacity” kilonova model. The solid (dotted) lines correspond to Bayes factors resulting from simulated data produced by the shock-interaction model (kilonova model). The black horizontal line indicates the $\log_{10}(\mathcal{B}) = 2$ threshold for decisive evidence.

provided by Piro & Kollmeier (2018), where they assume $s = 3$. The model parameters and prior distributions are again given in Table 2.

We note that for fiducial light curves and simulation of photometric data (below), Milky Way dust extinction is accounted for, but host galaxy dust extinction is not. In simulations here, dust extinction is applied assuming one consistent scenario, which is slightly more optimistic than average, causing more dimming than 40% of random pointings. This dust extinction especially affects the UV, and in this scenario a flat spectrum in the Dorado band is dimmed by $\sim 0.4$ Mag (AB).

3.3. Simulation of Data

Using all the fiducial light curves, we simulate photometric data to be used as data $D$ in the Bayesian analysis. These data are simulated using the instrument responses of Dorado in the UV and by Las Cumbres Observatory (LCO) in the optical r band.

The Dorado spacecraft was designed to accommodate a wide range of low-Earth orbits. We assume a noon–midnight Sun synchronous (polar) orbit with a 600 km altitude for the simulations described here.

*dorado-scheduling* can generate realistic observational sequences for GW localizations, including exclusion constraints (Sun, Moon, and Earth limb), as well as satellite downtime for passages through the South Atlantic Anomaly. The software can define optimized observing strategies based on the GW localization region and distance, as well as a (position-dependent) exposure time calculator (ETC).

For the simulation of Dorado photometric data, one set of representative observational cadences was derived using the *dorado-scheduling* (see footnote 11) software package. The first data point is observed at $\Delta t = 1.2$ hr (72 minutes) postmerger (to allow for time to upload to the spacecraft) and a fixed exposure time of 10 minutes every orbit (97 minutes cadence) on a single pointing.

Signal-to-noise estimates were derived using *dorado-sensitivity*, the ETC for the Dorado mission. *dorado-sensitivity* generates realistic foreground models for zodiacal light (based on spacecraft and target location), as well as airglow emission (based on location within the orbit). The fiducial light curve is folded through the Dorado effective area curve to generate the expected source counts and then compared with the background (including both foreground and source shot noise). For reference, for a 15 minute exposure, Dorado’s 5 $\sigma$ limiting magnitude for an isolated point source is typically $\sim 20.8$ mag (AB).

For ground-based optical observations only the r band is made use of. While more optical bands (such as $u$, $g$, and $i$) are available, we found that their inclusion minimally affected model selection and parameter estimation (compared to just the r band) and omitted them in exchange for reduced computational time. We similarly use the same detection schedule for all simulated events but starting at 12 hr and with a 12 hr cadence up to 48 hr. This choice was motivated by the time at which the first ground-based imaging of AT2017gfo was obtained (Coulter et al. 2017). To calculate this photometric data we use an ETC constructed using data of LCO instruments. LCO is a network of 25 telescopes at seven sites around the world, sensitive in optical and NIR wavelengths. Being purpose-built to observe transient events, it robotically schedules observations and leverages its global network to observe around the clock and make rapid observations of target of opportunities (ToOs), evading potential local weather limitations (Brown et al. 2013). From here onwards, we refer to these timings for the observation of UV and optical data as the “base case” for observation timing. Eventually we deviate from the base-case timing scenario when studying delayed UV data in Section 4.2.

4. Bayesian Analysis

This study employs *Dynesty* (Speagle 2020) for nested sampling (Skilling 2004, 2006). Nested sampling is a method for simultaneously estimating posterior probability $P(\theta|D, M)$ (see Equation (6)) and evidence $\mathcal{Z}$ (see Equation (7)). The full pipeline for simulation of photometric data and subsequent Bayesian analysis is publicly available on GitHub. The pipeline is also available in the persistent repository on Zenodo including input data to reproduce the analysis, and data products from the analysis to reproduce the figures. This section presents the results of the Bayesian analysis and is structured as follows: Section 4.1 presents the results of model selection and parameter estimation from separate satellite-based

11 https://github.com/nasa/dorado-scheduling/
12 https://github.com/nasa/dorado-sensitivity/
13 https://exposure-time-calculator.lco.global/
14 https://github.com/loadvorsman/kilonova-bayesian-analysis/
15 doi:10.5281/zenodo.7157982
UV data, ground-based optical data, and these photometric data jointly, all assuming the base-case observation timing scenario as defined in Section 3.3. Section 4.2 analyzes the effect of the delayed observation of the target.

4.1. Model Selection and Parameter Estimation for Rapid UV, Optical, and Joint Data

Figure 2 shows Bayes factors as a function of luminosity distance of the merger. In all cases up to 160 Mpc, the kilonova models can be confidently distinguished from the shock-interaction model using only satellite-based UV data. Conversely, the optical data are able to distinguish the models only up to 110 Mpc in the most optimistic scenario and \( \sim 40 \) Mpc in other scenarios. The combined UVO data allow for (marginally) better distinguishability than the satellite-based UV data.

Now turning to parameter estimation and its distance dependency, Figure 3 shows the posterior probability distributions (PPDs) for the "default" kilonova model at three selected luminosity distances: luminosity distance \( d_L \) = 40, 100, and 160 Mpc.
160 Mpc. Two out of the seven model parameters, \( v_{\text{transition}} \) and \( \kappa_{\text{low}} \), are well constrained by the UV photometric data and especially so at the most close-by distance at 40 Mpc. We note that these two parameters in part define the outer opacity zone of the ejecta outflow. Because the outer opacity zone is bright in UV\(^{16} \), we expect these parameters to be relatively well constrained by the UV photometric data. The remaining five parameters are not significantly constrained.

Figure 4 shows the PPD for the shock-interaction model. Even for 40 Mpc the parameters are constrained only slightly within prior ranges. As is evident from the figure, this lack in the constraining of parameters is due to parameter degeneracy in this model. We find the following degeneracy in the model: consider a set of parameters \( M_1, \kappa_1, \) and \( R_1 \) that produce some \( L_1, T_{\text{eff},1}, \) and \( r_{\phi,1} \). There exists another set of parameters, \( M_2 = \phi^{-1} M_1, \kappa_2 = \phi \kappa_1, \) and \( R_2 = \phi R_1 \), where \( \phi \) is some constant. Substituting these into Equations (3)–(5), all factors \( \phi \) cancel, and we are left with \( L_1 = L_2, T_{\text{eff},1} = T_{\text{eff},2}, \) and \( r_{\phi,1} = r_{\phi,2}. \) This means that the blackbody spectrum is identical for different parameters. Because of this degeneracy, parameters cannot be individually constrained even if observing in multiple bands. We note, however, that in the case of AT2017gfo, the \( R_{\text{shock}} \) could be independently constrained from the time delay between the GWs and the GRB. In such a case \( \kappa \) would become constrained, but a degeneracy remains between \( M_{\text{shock}} \) and \( v_{\text{shock}} \) (\( M_2 = \phi^{-1} M_1 \) and \( v_2 = \phi v_1 \)).

Figure 5 shows the results for the “default” kilonova model again (same as 40 Mpc in Figure 3) but now also including a comparison with ground-based optical photometric data and with combined data of both bands. In isolation, observations perform mostly similarly to satellite-based UV: most parameters are not tightly constrained except \( v_{\text{transition}} \), which is constrained reasonably well. \( \kappa_{\text{low}} \) is an exception to this similarity since it is well constrained for UV but not in optical. Notably, in combination ground-based optical and UV are complementary to each other, providing significant improvement compared to using either band in isolation. In that case, all parameters except \( n \) are well constrained.

4.2. Delayed UV Detection

The time it takes from the GW trigger to first on-target exposure (effective response time) should be as short as possible to capture the physics that govern the early postmerger system. This is especially relevant for the UV compared to optical and IR because the emission rises and fades more rapidly, which is \( \sim \) hours compared to \( \sim \) days and \( \sim \) weeks, respectively (Abbott et al. 2017b). Figure 6 shows the results for model selection using satellite-based UV photometric data, where the data set as a whole was shifted forward in time with various delays as indicated in the figure. Note that the case for data at 1.2 hr (72 minutes) corresponds to the base-case observation timing scenario (see Sections 3.3 and 4.1). If the first data are collected within 3.2 hr after the GW trigger, the shock-interaction and “default” light curves can be confidently identified up to 160 Mpc. For the “lower early opacity” kilonova model, this is only possible up to 130 Mpc. If the first data are collected within 5.2 hr, all light curves can be confidently identified up to at least 60 Mpc. Furthermore, if the first data are collected after 13.2 hr, confident model selection fails for 40 Mpc and beyond.

Figure 7 shows the results for parameter estimation for increasingly delayed photometric data. All parameters experience worsening constraints for increasing response time. Of the two parameters that were previously well constrained for satellite-based UV photometric data, \( v_{\text{transition}} \) is still well constrained even for data starting at 25.2 hr while \( \kappa_{\text{low}} \) is not well constrained beyond 13.2 hr. We posit that \( v_{\text{transition}} \) may be well constrained even with such delayed data because it affects both opacity zones, while \( \kappa_{\text{low}} \) only plays a role in defining the quicker-fading outer opacity zone.

5. Discussion and Conclusion

We have performed model selection and parameter estimation, assuming AT2017gfo-like “blue” emission produced by either kilonova or shock-interaction radiation and assuming observational capabilities of a UV satellite (Dorado) and an observation network (LCO). Our main findings are threefold:

First, we consider data under the base-case observation timing scenario where UV data start at 1.2 hr and optical at 12 hr. Our results suggest that satellite-based UV photometric data, unaided by ground-based optical follow-up, would be sufficient to distinguish these models for an event up to at least 160 Mpc for all considered scenarios. Conversely, ground-based optical photometric data only select models up to \( \sim 110 \) Mpc in the most optimistic scenario and has considerably worse performance (selection up to \( \sim 40 \) Mpc) in other scenarios. Combined UV/photometric data only marginally improve model selection beyond what is possible with only UV data.

Second, we find that the UVO photometric data as described above but measured jointly allow the full set of parameters (save \( n \), which defines steepness of the ejecta velocity profile) of our kilonova model to be well constrained. In comparison, photometric data from either UV or optical alone constrain

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\(^{16}\)At least for these fiducial parameters such that the light curves resemble AT2017gfo.
smaller subsets of the parameters and with reduced accuracy and precision. This result suggests that multiple-wavelength detections are essential for constraining early ejecta geometry and opacity.

Third, looking at delayed observation, we find that Dorado-like satellite-based UV data allow discernment between the models if the first data are observed no later than 3.2 hr after the GW trigger for all light curves up to at least 130 Mpc. In addition, for first data at 5.2 hr all considered models can be discerned up to at least 60 Mpc. These results indicate that rapid on-target observations on the order of a few hours is necessary for distinguishing the kilonova from shock-interaction models with Dorado.

To place these results in a broader context, we comment on prospects for planned wide-field (>10 deg²) UV instruments to detect and characterize EM counterparts during the O5 observation run of GW observatories: Advanced LIGO, Virgo, and KAGRA (HLVK) in 2026 and beyond. Planned missions ULTRASAT (launch 2025) and UVEX (launch ~2028) overlap at least partially with O5. We focus here on O5 because no planned wide-field UV mission will be launched in time to overlap with O4 (Dorado was targeted for overlap with O5), and the plans for the GW network remain undetermined beyond O5.

Figure 5. Similar to Figure 3 but now comparing results for parameter estimation using ground-based optical photometric data (solid), satellite-based UV photometric data (dashed-dotted), and joint data (dashed), assuming the base-case observation timing scenario or an event at 40 Mpc.
To start with, the wide-field UV mission ULTRASAT is more sensitive than Dorado with a limiting magnitude of $\sim 22.3$ (5σ, AB, $3 \times 300$ s exposure) and a larger FOV at 200 deg$^2$ (Asif et al. 2021). Because of this and ULTRASAT’s ability to point to a given ToO within 30 minutes (Sagiv et al. 2014), it is both sensitive and quick enough to provide the UV data for model selection and constraints as suggested by simulations here. Second, UVEX responds within $\sim 3$ hr and is even more sensitive with a limiting magnitude of 25 (AB, 5σ) but has a smaller FOV of 12 deg$^2$. In addition, UVEX will provide additional detail in the light curves and spectra through its two (far- and near-UV) sensors and onboard spectroscope (Kulkarni et al. 2021). The multiband coverage should lead to greater diagnostic power, both in model selection and parameter estimation. However, quantifying this improvement is beyond the scope of this work. We note that it is to be expected that the improved sensitivities of both missions improve model selection and parameter estimation for all events but also increase detection rate due to an enlarged significant detection horizon.

To discuss detection rate in further detail, we note that simulations of GW detections in O5 were done by Petrov et al. (2022). From their simulated data set (Singer 2021) we compute that, of BNS events within 160 Mpc, 69% are localized within 100 deg$^2$, which would be easily followed up by Dorado within a single orbit. The fraction of events that meet both distance and localization criteria, multiplied by the annual detection rate (190; from Petrov et al. 2022) gives an annual detection rate of $\sim 3.2$. If we include events up to 400 Mpc, we find that still 46% of events are localized within 100 deg$^2$, corresponding to an annual rate of $\sim 20$ events. Thus, for BNS mergers, if we assume similar brightness to AT2017gfo, we expect an annual detection rate of $\sim 3.2$ of which shock interaction and kilonova radiation could be distinguished and kilonova ejecta parameters constrained with a Dorado-like satellite. For BHNS mergers, which have not been simulated here, the expected number of detected EM counterparts should be much lower as only a small region of BHNS parameter space will lead to disruption of the NS (Foucart 2020).

Finally, we remark on the various simplifying assumptions made in this study that may affect the robustness of the above findings. To start with, throughout this work we have made the assumption that the EM counterparts of all BNS mergers are similar to AT2017gfo. This introduces an “AT2017gfo-bias” in our predictions for the ability of a future UV satellite to achieve science goals. It is as of yet uncertain how representative AT2017gfo is for the actual kilonova population, and O4 and O5 are expected to be diverse, for example, due to binary properties, such as mass-ratio and spins, but also postmerger properties such as remnant outcome (e.g., Kawaguchi et al. 2020) and jet–ejecta interaction (e.g., Klion et al. 2021). These are expected to have an effect on ejecta geometry and composition, which in turn affect the brightness and color of light curves.

Another assumption underlying this study is that both models assume isotropic ejecta. However, the photon emission as well as composition and geometry of the ejecta are not expected to be spherically symmetric (e.g., Metzger 2017; Heinzel et al. 2021). Other models that include the inclination angle, such as the grid of 2D simulations presented by Wollaeger et al. (2021), would allow for a more representative study covering the angular dependence of UV light curves. Still, Heinzel et al. (2021) recommend the inclusion of $\sim 1$ mag uncertainties for kilonova models used in Bayesian studies relating to inclination angle to capture yet unknown systematic model uncertainties.

We also note that a significant source of uncertainty remains in the nuclear physics taking place in these high-energy events. For example, Zhu et al. (2022) find that uncertainties in nuclear inputs lead to typically 1 order of magnitude variation in inferred nuclear heating, bolometric luminosity, and ejecta mass.

Another point is that this study assumes that optical follow-up starts at 12 hr after the GW trigger (as was the case with AT2017gfo), but this does not have to be the case for future events. Preliminary calculations indicate that earlier optical data improve parameter estimation and model selection results. A comprehensive study on the effect on parameter recovery and model selection for delayed data in various wavelengths would help define timing requirements for future follow-up efforts. We leave this to future work.

Lastly, although the scope of this study was limited to shock interaction and kilonova radiation, we note that a more comprehensive study may include additional radiation scenarios, such as a neutron precursor or winds driven by a long-lived remnant, and also a combination of emission channels.

In conclusion, under the assumption of the first UV data by a Dorado-like satellite observed within 1.2 hr, these simulations...
show that UV data offer a unique window to distinguish the processes governing the early postmerger system. In addition to aforementioned UV data complemented by optical data starting at 12 hr, we find that the kilonova emission model parameters can be constrained up to at least 160 Mpc, unlocking a fuller understanding of the geometry and opacity of the ejecta outflow. Finally, considering only UV data by a Dorado-like satellite but now examining delayed observation, we find the competing emission models are distinguishable up to at least 130 (60) Mpc if the first data are obtained within 3.2 (5.2) hr.

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Software: Python language (Oliphant 2007), NumPy (van der Walt et al. 2011), SciPy (Jones et al. 2001),

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**Figure 7.** Similar to Figure 3 but now with the satellite-based UV photometric data at 40 Mpc shifted in time such that the first data point is obtained at 1.2, 13.2, and 25.2 hr after the GW trigger.
