Spitzer Space Telescope Infrared Observations of the Binary Neutron Star Merger GW170817

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Abstract

We present Spitzer Space Telescope 3.6 and 4.5 μm observations of the binary neutron star merger GW170817 at 43, 74, and 264 days post-merger. Using the final observation as a template, we uncover a source at the position of GW170817 at 4.5 μm with a brightness of 22.9 ± 0.3 AB mag at 43 days and 23.8 ± 0.3 AB mag at 74 days (the uncertainty is dominated by systematics from the image subtraction); no obvious source is detected at 3.6 μm to a 3σ limit of >23.3 AB mag in both epochs. The measured brightness is dimmer by a factor of about 2–3 times compared to our previously published kilonova model, which is based on UV, optical, and near-infrared data at <30 days. However, the observed fading rate and color (m3.6–m4.5 > 0 AB mag) are consistent with our model. We suggest that the discrepancy is likely due to a transition to the nebular phase, or a reduced thermalization efficiency at such late time. Using the Spitzer data as a guide, we briefly discuss the prospects for observing future binary neutron star mergers with Spitzer (in the Laser Interferometer Gravitational-Wave Observatory (LIGO)/Virgo Observing Run 3) and the James Webb Space Telescope (in LIGO/Virgo Observing Run 4 and beyond).

Key words: gravitational waves – infrared: general – stars: neutron

1. Introduction

The gravitational wave discovery of the binary neutron star (BNS) merger GW170817 (Abbott et al. 2017b), and the subsequent identification of its electromagnetic counterpart (Abbott et al. 2017a), provided the first multi-messenger view of a compact object merger and its aftermath. In the ultraviolet, optical, and near-infrared (hereafter, UVOIR) the emission was observed in the first month post-merger, before the source became Sun-constrained. The UVOIR emission was produced by the radioactive decay of r-process nuclei synthesized in the merger ejecta, a so-called kilonova (e.g., Li & Paczyński 1998; Rosswog et al. 1999; Metzger et al. 2010; Roberts et al. 2011; Metzger & Berger 2012; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013).

From these observations, most authors concluded that GW170817 produced at least two distinct non-relativistic ejecta components: a rapidly evolving “blue” component dominated by light r-process nuclei (atomic mass number A < 140) with a mass of ≈0.02M⊙ and a velocity of ≈0.3c; and a more slowly evolving “red” component dominated by heavy r-process elements (A > 140, including lanthanides) with a mass of ≈0.05M⊙ and a velocity of ≈0.15c (e.g., Villar et al. 2017; although see Smartt et al. 2017; Waxman et al. 2017). The multi-component nature of the ejecta is also evident in optical and near-infrared (NIR) spectroscopic observations (Chornock et al. 2017; Nicholl et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017). Subsequently, X-ray, radio, and optical observations of the non-thermal afterglow provided insight into the production of relativistic ejecta (Alexander et al. 2017; Gottlieb et al. 2017; Haggard et al. 2017; Hallinan et al. 2017; Lazzati et al. 2017; Margutti et al. 2017; Troja et al. 2017; Alexander et al. 2018; D’Avanzo et al. 2018; Dobie et al. 2018; Lyman et al. 2018; Margutti et al. 2018; Mooley et al. 2018; Nynka et al. 2018; Ruan et al. 2018; Troja et al. 2018).

At ≲10 days the kilonova spectral energy distribution (SED) peaked in the NIR, with a blackbody temperature of ≲1300 K, and hence an expected substantial contribution into the mid-infrared (MIR; Chornock et al. 2017; Nicholl et al. 2017; Kasliwal et al. 2017). Here, we present the full set of Spitzer Space Telescope infrared (IR) observations of GW170817, obtained at 43, 74, and 264 days post-merger, which extend the kilonova observations to 3.6 and 4.5 μm (see Lau et al. 2017); we uncover clear detections at 4.5 μm. In Section 2 we present the observations and our data analysis, image subtraction, and photometry procedures. We compare the results to our kilonova models from Villar et al. (2017) in Section 3. Motivated by the results, in Section 4 we discuss the prospects for IR observations of future events with Spitzer and the James Webb Space Telescope (JWST).

All magnitudes presented in this Letter are given in the AB system and corrected for Galactic reddening with E(B–V) = 0.105 mag (Schlafly & Finkbeiner 2011). All uncertainties are reported at the 1σ level. We assume negligible reddening contribution from the host galaxy (Blanchard et al. 2017), and a luminosity distance to NGC 4993 of 40.7 Mpc (Cantiello et al. 2018).
2. Observations and Data Analysis

We downloaded public Spitzer (Werner et al. 2004) observations of GW170817 taken on 2017 September 29, 2017 October 30, and 2018 May 8 with the InfraRed Array Camera (IRAC; Fazio et al. 2004) in the 3.6 and 4.5 μm bands during the “warm” Spitzer mission (Director’s Discretionary Time Program 13202; PI: Kasliwal); see Table 1. Each visit consisted of 466 frames with exposure times of 30 s per frame, for a total on-source time of ≈3.9 hr in each band. We processed the images using standard procedures in Mopex (Makovoz & Marleau 2005) to generate mosaic images. Mopex cleans the images of cosmic rays and applies appropriate distortion corrections before drizzling the images. We used a drizzling factor of 0.8 and an output pixel scale of 0".4. We compare the native astrometry to seven Two Micron All-Sky Survey (2MASS) point sources in the field, and find that the astrometric solution is good to about 1 pixel.

The observations were reduced with the HOTPANTS package (Alard 2000; Becker 2015), using the 2018 May 8 observations as a template in each band. We note that at 264 days post-merger, the emission from the relativistic ejecta (which dominates in the radio and X-ray bands) has $m_{3.6} = 25.9$ and $m_{4.5} = 25.7$ mag (Alexander et al. 2018; Margutti et al. 2018; Xie et al. 2018), more than an order of magnitude below the expected brightness of the kilonova emission, and well below the detection level of the Spitzer data. A composite 3.6 and 4.5 μm image, and the subtracted 4.5 μm image at 43 days are shown in Figure 1. A point source is apparent in the difference image.

Although HOTPANTS computes and utilizes a spatially variable convolution kernel, and is therefore able to match dissimilar point spread functions (PSFs), we find that the location of GW170817 is heavily contaminated by residual artifacts from the bright host galaxy. To remove the remaining contamination, we first mask the source location in the difference image with a region the size of the expected PSF (≈5 pixels). We then smooth the masked image with a Gaussian kernel, interpolating across the masked region. We use a kernel standard deviation of one pixel (but find that the kernel width has little effect on our results). We then subtract the smoothed image from the original difference image to isolate the point source. The resulting final 4.5 μm images from 43 and 74 days are shown in Figure 1 and clearly reveal the presence of a point source at the location of GW170817.

We measure the brightness of the source using both fixed aperture photometry and PSF-fitting assuming a Gaussian PSF. We injected fake point sources around the host galaxy at a similar offset to that of GW170817 to quantify the systematic uncertainties of the subtraction methods and photometry. For the observations with a detected source at the location of GW170817 (4.5 μm), we specifically injected fake sources of the same measured magnitude. For each injected source, we executed the same method of smoothing and subtraction from a masked image. We used the spread in the recovered magnitudes as our overall uncertainty. For the observations without a significantly detected source (3.6 μm), we injected sources with a range of fluxes to determine 3σ upper limits. The results are summarized in Table 1. We additionally confirmed that the 4.5 μm detection is not an artifact of the subtraction process or the IRAC PSF by searching for sources at the same relative location as the GW170817 counterpart around a nearby saturated star within the field of view, following the same procedure. We did not find any significant sources around the star.

The detected source at 4.5 μm has $22.9 ± 0.3$ mag at 43 days and $23.8 ± 0.3$ mag at 74 days post-merger. The source is detected with a signal-to-noise ratio (S/N) of ≈10 at 43 days and ≈5 at 74 days. However, the final uncertainties are dominated by systematic effects, as determined from the spread in magnitudes for the injected fake point sources. We do not detect a source at 3.6 μm in either epoch to a 3σ limit of $≥23.3$ mag. The exact significance of our (non)detections may be better constrained through other methods (e.g., Zackay et al. 2016).

3. Comparison to a Kilonova Model

We compare the observations to our three-component kilonova model, which was previously used to fit all available UVOIR photometry (Villar et al. 2017); see Figure 2. Each component is characterized by a unique gray opacity roughly corresponding to its lanthanide fraction (Tanaka et al. 2018), and is independently described by a blackbody SED. The blackbody SEDs cool as a function of time until they reach a minimal “temperature floor,” at which point we assume that the photosphere recedes into the ejecta, at a constant temperature. At late times (≳10 days), our three-component model predicts that the light curve is dominated by the intermediate $r$-process component and that this component has reached its temperature floor of $≈1300$ K, somewhat cooler than the lowest lanthanide ionization temperature (e.g., Kasen et al. 2013).

We find that our model overpredicts the Spitzer measurements at 43 and 74 days by about a factor of $≈3$ (1.2 mag) and $≈2.5$ (1 mag), respectively (Figure 2). However, the decline rate between the two measurements is in good agreement with the model prediction. Similarly, the temperature implied by the flat or red color in the 3.6 and 4.5 μm bands ($≤1200$ K) is consistent with the temperature floor in our model. We observe a similar late-time deviation from our model in the $K_s$-band (2.2 μm) at $≥20$ days.

Assuming a blackbody SED with $T = 1200$ K we find that the bolometric luminosity implied by the 4.5 μm detections is $≈6 × 10^{38}$ erg s$^{-1}$ and $≈2 × 10^{38}$ erg s$^{-1}$ at 43 and 74 days, respectively. This is consistent with the drop off in bolometric luminosity starting at $≈10$ days, when the estimated bolometric luminosity is $≈2 × 10^{40}$ erg s$^{-1}$ (Cowperthwaite et al. 2017; Waxman et al. 2017; Arcavi 2018).

Relaxing some of the assumptions in our model may eliminate the brightness discrepancy. For example, at the time of the Spitzer observations the kilonova is likely transitioning into the nebular phase, and the blackbody SED approximation may break down. Using the parameters of the dominant intermediate-opacity component of our model (Villar et al. 2017), we find that at 43 days the optical depth is $τ ≈ 1$, suggesting that the ejecta are
becoming optically thin. Additionally, the shape of the late-time light curve is also dictated by the time-dependent thermalization efficiency of the merger ejecta (Barnes et al. 2016). As the steep decline of the thermalization efficiency at \( t \lesssim 20 \) days will better capture the lower observed fluxes in the \( K_s \) and \( \text{Spitzer} \) bands. The thermalization is highly dependent on the nuclear mass models assumed (see e.g., Barnes et al. 2016; Rosswog et al. 2017), and is uncertain by almost an order of magnitude at \( t \lesssim 1 \) month. Our observations would imply an efficiency of \( f_{\text{tot}} \approx 0.1 \) at \( t > 40 \) days.

We also consider the possibility that the observed IR emission is due to reprocessing of bluer kilonova emission by newly formed dust. The warm temperature implied by our observations requires carbon-based dust, due to its high condensation temperature \( T_c \approx 1800 \) K; Takami et al. 2014. We fit a modified blackbody to the \( \text{Spitzer} \) photometry at day 43, assuming \( m_{3.5} \approx m_{4.5} \) (following Equations (1) and (2) of Gall et al. 2017). We find that the carbon dust mass required to reproduce the observed luminosity is \( \approx 5 \times 10^{-7} M_\odot \). However, Gall et al. (2017) explored a range of theoretical kilonova wind models and found that, at most, \( \sim 10^{-9} M_\odot \) of carbon dust can be produced. We therefore conclude that the observed IR emission is not due to dust reprocessing.

### 4. Implications for IR Observations of Future BNS Mergers

The \( \text{Spitzer} \) detections of GW170817 at 43 and 74 days post-merger indicate that future BNS mergers should be observed at
IR wavelengths. Indeed, taking our models at face value, at least in the well-characterized regime at \( \lesssim 20 \) days, it appears that the peak of the kilonova emission shifts into the NIR/MIR bands at \( \gtrsim 10 \) days. This suggests that significant effort should be focused on robust characterization of the IR emission of kilonovae. This will provide numerous benefits, including a more accurate determination of the bolometric luminosity and therefore total r-process ejecta mass, improved measurements of the r-process opacity at long wavelengths, observational constraints on the late-time thermalization efficiency, and continued insight into BNS mergers as sites of cosmic r-process production.

Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO)/Virgo (ALV) Observing Run 3 (O3) is expected to begin in early 2019 and span a full year, with an expected BNS merger detection distance of \( \lesssim 120 \) Mpc. The timing of O3 overlaps favorably with Spitzer Cycle 14 (the final Spitzer cycle), and the sensitivity should be sufficient to detect events with a similar IR luminosity to GW170817 in the first \( \approx 40 \) days to \( \lesssim 120 \) Mpc. For example, observations of about 9 hr on-source can achieve 5\( \sigma \) limiting magnitudes \(^4\) of \( m_{3.6} \approx 25.5 \) mag and \( m_{4.6} \approx 25 \) mag, assuming no significant contamination from host galaxy subtraction. In reality, host galaxy contamination may prove to be problematic for dim events to the \( \approx 10\% \) photometry level. A full exploration of these systematics is not possible with only one observed event.

Beyond O3 (2021 and later), the ALV network is expected to achieve design sensitivity, with typical BNS merger detections to \( \lesssim 200 \) Mpc and a maximal detection distance of \( \approx 450 \) Mpc (for favorably oriented and positioned BNS mergers). The timing is ideal for overlap with JWST, which will be able to provide NIR and MIR spectra. In the NIR, NIRSpec can produce low-resolution (\( R \approx 100 \)) spectra at 0.6–5.3 \( \mu \)m; this resolution is sufficient for kilonovae given the typical velocities of \( \sim 0.1–0.3 \)c. In particular, spectra with S/N \( \gtrsim 50 \) can be obtained near peak for a GW170817-like kilonova to 450 Mpc in just 1 hr of on-source time. At later times, BNS mergers could be tracked to \( \approx 40 \) days at \( \approx 200 \) Mpc with S/N \( \approx 10 \) in about 6 hr of on-source time.

In the MIR, the Mid-infrared Instrument (MIRI) can produce low-resolution (\( R \approx 40–160 \)) spectra covering 5–14 \( \mu \)m. In particular, S/N \( \approx 10–20 \) at 5–9 \( \mu \)m (and lower S/N at longer wavelengths) can be achieved for a GW170817-like kilonova near peak to \( \approx 450 \) Mpc with \( \approx 5 \) hr of on-source time. At late times (\( \approx 40 \) days), MIRI can produce S/N \( \approx 5 \) spectra at 5–7 \( \mu \)m to \( \approx 100 \) Mpc.

We do not yet know the full range of brightnesses and SEDs of kilonovae, as well as the potential contribution of dust reprocessing, but the discussion above illustrates that NIR/MIR characterization of kilonovae can be achieved with Spitzer in ALV O3 and with JWST when ALV reaches design sensitivity. This can be achieved with a modest time investment, but will require target-of-opportunity response to BNS mergers.

5. Conclusions

We present Spitzer IR observations of the kilonova associated with GW170817 spanning to 264 days post-merger. We detect the kilonova at 4.5 \( \mu \)m at 43 and 74 days post-merger with a brightness of \( \approx 22.9 \) and \( \approx 23.8 \) mag, respectively. We do not identify a confident detection at 3.6 \( \mu \)m, to a 3\( \sigma \) upper limit of \( \gtrsim 23.3 \) mag. The inferred color of the kilonova indicates that the ejecta has cooled to \( \lesssim 1200 \) K at these late times. These magnitudes are fainter than an extrapolation of our model to the UVOIR data at \( \lesssim 30 \) days, highlighting the need for improved models at late times (for example, the details of the ejecta thermalization). Finally, we show that future BNS mergers with kilonovae similar to GW170817 will be detectable with Spitzer to 120 Mpc at 40 days post-merger, and will be accessible to NIR and MIR spectroscopy with JWST to \( \approx 450 \) Mpc at peak and to \( \approx 100–200 \) Mpc at 40 days post-merger (and to later times with JWST imaging).

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\(^4\) See Spitzer ETC (http://ssc.spitzer.caltech.edu/warmmission/propkit/pet/senspet/).
