CONTINUED RADIO OBSERVATIONS OF GW170817 3.5 YEARS POST-MERGER

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ABSTRACT

We present new radio observations of the binary neutron star merger GW170817 carried out with the Karl G. Jansky Very large Array (VLA) more than 3 yrs after the merger. Our combined dataset is derived by co-adding more than ≈ 32 hours of VLA time on-source, and as such provides the deepest combined observation (RMS sensitivity ≈ 0.99 μJy) of the GW170817 field obtained to date at 3 GHz. We find no evidence for a late-time radio re-brightening at a mean epoch of t ≈ 1200 d since merger, in contrast to a 2-3 σ excess observed at X-ray wavelengths at the same mean epoch. Our measurements agree with expectations from the post-peak decay of the radio afterglow of the GW170817 structured jet. Using these results, we constrain the parameter space of models that predict a late-time radio re-brightening possibly arising from the high-velocity tail of the GW170817 kilonova ejecta, which would dominate the radio and X-ray emission years after the merger (once the structured jet afterglow fades below detection level). Our results point to a steep energy-speed distribution of the kilonova ejecta (with energy-speed power law index α ≳ 5). We suggest possible implications of our radio analysis, when combined with the recent tentative evidence for a late-time re-brightening in the X-rays, and highlight the need for continued radio-to-X-ray monitoring to test different scenarios.

Subject headings: GW170817, Kilonova afterglow: general — radio continuum: general

INTRODUCTION

GW170817 has been a milestone event for transient multi-messenger studies. It was the first binary neutron star (NS) merger observed by the LIGO and VIRGO detectors (Abbott et al. 2017), and so far it remains the only binary NS system from which gravitational waves (GWs) and a multi-wavelength (radio to gamma-ray) counterpart have been discovered (Abbott et al. 2020; Kasliwal et al. 2020; Paterson et al. 2020). The GW170817 NS-NS merger occurred at 12:41:04 on 2017 August 17 UTC, and its GW detection was followed by the detection of a γ-ray burst (GRB) by the Fermi and INTEGRAL satellites, ≈ 2 s after the merger. UV/optical/IR instruments subsequently identified the so-called kilonova counterpart (AT2017gfo), in the galaxy NGC 4993 at a distance of ∼ 40 Mpc, making GW170817/GRB 170817a the closest short GRB with known redshift (e.g., Arcavi et al. 2017; Chornock et al. 2017; Coulter et al. 2017;Cowperthwaite et al. 2017; Drout et al. 2017; Kasliwal et al. 2017; Kasen et al. 2017; Kilpatrick et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017; Tanvir et al. 2017; Valenti et al. 2017). Observations of the quasi-thermal UV/optical/IR emission from the GW170817 slow (≈ 0.1c – 0.3c), neutron-rich, kilonova ejecta were successful in verifying that mergers of NSs in binaries are production sites of heavy elements such as gold and platinum (e.g., Kasliwal et al. 2017; Kasen et al. 2017; Pian et al. 2017; Metzger 2017).

In addition to the quasi-thermal kilonova emission, a delayed non-thermal (synchrotron) afterglow from GW170817/GRB 170817a was first observed in the X-rays 9 days after the merger by the Chandra observatory (e.g., Troja et al. 2017; Haggard et al. 2017; Margutti et al. 2017). A radio afterglow detection with the Karl G. Jansky Very Large Array (VLA) followed, about two weeks after the merger (Hallinan et al. 2017). Further radio observations of the source proved decisive in narrowing down the morphology of the jet (Corsi et al. 2018; Dohie et al. 2018; Alexander et al. 2017; Margutti et al. 2018; Mooley et al. 2018a,b, Hajela et al. 2019), ruling out the simple uniform energy-speed (top-hat) ejecta in favour of a structured jet, where the ejecta velocity varies with the angle from the jet axis (Mooley et al. 2018c; Lazzati et al. 2018; Ren et al. 2020). These observations, with the help of hydrodynamic simulations (Lazzati et al. 2018; Nakar et al. 2018), set constraints on the opening angle of the jet core (≲ 5 deg), the observer’s viewing angle (≈ 15 – 30 deg), the isotropic equivalent energy (∼ 10^{52} erg) and the interstellar medium (ISM) density (∼ 10^{-4} − 0.5 cm^{-3}).

The extended radio follow-up of GW170817 up to 2.1 years after the merger had shown that the radio emission from the structured jet had faded below typical flux density sensitivities that can be reached with the VLA in a few hours of observing (Makkathini et al. 2020). Several theoretical scenarios, however, predict the possible emergence at late times of detectable electromagnetic emission associated with the afterglow of the kilonova ejecta itself (e.g., Nakar & Piran 2011; Kathirgamaraju,...
et al. 2019; Hotokezaka et al. 2018; Margalit & Piran 2020). Indeed, numerical simulations show that during the NS-NS merger, a modest fraction of a solar mass is ejected from the system, and the total ejecta mass and velocity distribution of such ejecta depend on the total mass, mass ratio, and the nuclear equation of state (EoS) of the compact objects in the binary. While optical-UV observations are mostly sensitive to the low-end of the ejecta velocity distribution, radio (and X-rays) can probe the fastest moving ejecta tail, shedding light on whether NS-NS ejecta are broadly distributed in energy and velocity (as simulations seem to suggest) and providing indirect constraints on the nuclear EoS.

Tentative evidence for a very late-time re-brightening possibly associated with the kilonova afterglow of GW170817 has recently been reported in the X-rays (Hajela et al. 2020a, 2021; Troja et al. 2020). On the other hand, relatively shallow observations (RMS $\approx 4.3 \mu$Jy) with the VLA at 3 GHz had reported a lack of radio detection contemporaneous with the X-ray late-time re-brightening (Alexander et al. 2020). This radio non-detection was interpreted to be compatible with expectations from the simplest extrapolation of the X-ray excess to the radio band (Alexander et al. 2020). Here, we use deep VLA observations to show that the lack of a radio detection to much deeper limits constrains kilonova ejecta models to a relatively steep energy-velocity ejecta profile.

Our work is organized as follows. We report our new observations in §2; in §3 we discuss our results within the kilonova afterglow model; finally, in §4 we conclude with a summary.

### TABLE 1 VLA late-time observations of the GW170817 field.

See text for details on RMS measurements.

| Date (UT) | $\nu$ (GHz) | VLA config. | Time on-source (hr) | RMS (\mu Jy) | VLA program | PI |
|-----------|-------------|-------------|--------------------|-------------|-------------|----|
| 2020 Sep 19 | 3.0 | B | 2 h 43 m 24 s | 4.6 | 20A-185 | Balasubramanian |
| 2019 Sep 20 | 3.0 | B | 2 h 43 m 27 s | 5.8 | 20A-185 | Balasubramanian |
| 2020 Dec 15 | 3.0 | A | 3 h 24 m 14 s | 3.5 | SL0449 | Margutti |
| 2020 Dec 27 | 3.0 | A | 3 h 24 m 12 s | 3.3 | SL0449 | Margutti |
| 2021 Jan 10 | 3.0 | A | 2 h 41 m 34 s | 3.7 | 20B-208 | Balasubramanian |
| 2021 Jan 16 | 3.0 | A | 2 h 38 m 34 s | 3.6 | 20B-208 | Balasubramanian |
| 2021 Feb 02 | 3.0 | A | 3 h 24 m 16 s | 3.3 | SM0329 | Margutti |
| 2021 Feb 04 | 3.0 | A | 2 h 38 m 38 s | 4.1 | 20B-472 | Corsi |
| 2021 Feb 05 | 3.0 | A | 2 h 41 m 31 s | 4.0 | 20B-472 | Corsi |
| 2021 Feb 06 | 3.0 | A | 2 h 41 m 34 s | 3.8 | 20B-472 | Corsi |
| 2021 Feb 08 | 3.0 | A | 2 h 41 m 36 s | 4.0 | 20B-472 | Corsi |
| 2021 Feb 10 | 15.0 | A | 2 h 40 m 52 s | 1.9 | SM0329 | Margutti |

2. OBSERVATIONS AND DATA REDUCTION

As we describe in what follows, we have processed new and archival data of GW170817 obtained at radio and X-ray wavelengths between 2020 September and 2021 February. The full panchromatic afterglow light curve of GW170817 is available for download on the web.\footnote{https://github.com/kmooley/GW170817/ or http://www.tauceti.caltech.edu/kunal/gw170817/}

#### 2.1. Radio Observations

Radio observations of the GW170817 field were carried out with the VLA on the dates listed in Table 1 at S band (2–4 GHz, nominal central frequency of 3 GHz) with the array in its B (September 2020) and A configurations (December 2020 - February 2021). Each observation was co-added and interactively imaged as above with one Taylor term ($n_{\text{terms}}=1$) and a cleaning threshold of 4 $\mu$Jy. We find no significant (> 3×RMS) excess in a region of one synthesized beam around the position of GW170817 in any of the individual images. Next, we co-added and interactively imaged as above ($n_{\text{terms}}=1$ and $\text{robust}=0.5$) all A-configuration 3 GHz VLA observations listed in Table 1. An RMS of 1.3 $\mu$Jy was reached at 2.8 GHz (Table 2) within a region of size approximately equal to 20 synthesized beams centered on the position of GW170817. Within one synthesized beam centered on the location of GW170817, we measured an $\text{imstat}$ peak flux density value of $\approx 2.8 \mu$Jy at 2.8 GHz. With this procedure, several of the bright, extended sources present in the field left substantial deconvolution residuals. Thus, to mitigate the effects of deconvolution residuals, test the robustness of our measurement, and further improve our sensitivity, we imaged all 3 GHz data (both A and B configurations of the VLA) listed in Table 1 non-interactively with two Taylor terms ($n_{\text{terms}}=2$), robust weighting ($\text{robust}=0.5$), single phase-only selfcal (solution interval of 4 minutes), and a cleaning threshold of 4 $\mu$Jy. This yielded an image RMS noise of 0.99 $\mu$Jy (in a region of size equal to 20 synthesized beams around the position of GW170817; theoretical thermal noise $\approx 0.85 \mu$Jy) and a peak flux density value of 2.86 $\mu$Jy (Table 2) within one synthesized beam centered on the location of GW170817.

A late-time VLA observation of the GW170817 field was also carried out in U band (nominal central frequency of 15 GHz) on 10 February 2021 (Table 1). We calibrated this dataset and interactively imaged the field (with $n_{\text{terms}}=1$ and $\text{robust}=0.5$). No significant emission is found at the location of GW170817 (Table 2). The RMS measured in a region of size equal to 20 synthesized beams centered around the position of GW170817 is of $\approx 1.9 \mu$Jy at 15 GHz.
2.2. X-ray Data

We reprocessed and analyzed the Chandra ACIS-S observations of the GW170817 field obtained between 2020 December 10 and 2021 January 27 (obsIDs 22677, 24887, 24888, 24889, 23870, 24923, 24924; 150.5 ks, PI Margutti) using the same procedure described in Makhathini et al. (2020). For observations where the source was not apparent, we used the relative position of the other X-ray sources in the field of view to determine the source extraction region. By combining the spectral products of all 7 observations and fitting the data with an absorbed power-law model where hydrogen column density $N_H$ has been fixed to the Galactic value and the photon index $\Gamma = 1 - \beta$ has been fixed to 1.57 (Makhathini et al. 2020), we find an unabsorbed flux density of $(2.1^{+0.7}_{-0.6}) \times 10^{-4} \mu\text{Jy}$ at $2.4 \times 10^{17} \text{Hz}$ (1 keV; 1σ uncertainty). To investigate if $\Gamma$ is different from 1.57, we refitted the Chandra data leaving $\Gamma$ as a free parameter. From the 2020 December–January 2021 data we find $\Gamma = 2.16^{+1.18}_{-1.01}$. If we additionally combine the 96.6 ks of data obtained in 2020 March, we get $\Gamma = 0.98^{+0.77}_{-0.76}$ (90% uncertainties). Hence, in both cases, the value of $\Gamma$ is consistent (well within the 90% confidence interval) with $\Gamma = 1.57$. Our results are also consistent with Hajela et al. (2020a, 2021; Troja et al. 2020).
DISCUSSION

As evident from Figure 1, our late-time radio observations of GW170817 do not provide evidence for radio emission in excess to what is expected from the very late time tail of a structured jet afterglow model (black solid line). The X-ray observations, on the other hand, suggest a more pronounced statistical fluctuation or the possible emergence of a new component at higher frequencies (bottom panel in Figure 1).

The radio-to-X-ray spectral index as derived from the measured ratio of the late-time radio-to-X-ray flux densities (see Table 2) is $-0.523 \pm 0.026$, within $\approx 1.8\sigma$ of the value adopted in Figure 1 ($-0.56\pm 0.002$) derived by Makhathini et al. (2020). Thus, while current measurements still carry too large uncertainties for claiming any clear evidence for a change in spectral behavior at late times, the lack of a radio detection together with the tentative X-ray excess would suggest a flattening of the radio-to-X-ray spectrum at late times.

In general terms, it is not difficult to envision a scenario in which the electron index ($p$) for the ejecta responsible for the late-time X-ray excess differs from the one used to model the structured jet afterglow at earlier times ($p \approx 2.07 - 2.14$; Makhathini et al. 2020). The predictions of Fermi particle acceleration imply that the power-law index $p$ expected at non-relativistic shock speeds is close to $p \approx 2$, while at ultra-relativistic velocities one can have $p \approx 2.2$ (e.g., Sironi et al. 2015, and references therein). Thus, a flattening of the radio-to-X-ray spectral index in GW170817, if confirmed by further follow-up, could support the idea that a non-relativistic ejecta component is starting to dominate the emission.

Differently from the above theoretical predictions for particle acceleration, non-relativistic ejecta observed in radio-emitting core-collapse supernovae typically have $p = 2.5 - 3.2$ (e.g., Chevalier 1998), pointing to steeper radio-to-X-ray spectra than that suggested by the X-ray excess observed in GW170817. Cases where a transition of the ejecta from the relativistic to the non-relativistic regime has been observed include GRB030329 (e.g., Frail et al. 2005; van der Horst et al. 2008) and TDE Swift J1644+57 (Cendes et al. 2021). These two cases pointed to a slowly-increasing or constant value of $p$ in the relativistic-to-non-relativistic transition, which again would correspond to a spectral steepening rather than a spectral flattening.

One key difference between GW170817 and other non-relativistic flows is that we have seen a single power-law spectrum from radio, optical, and X-rays, i.e. synchrotron radiation from electrons with different Lorentz factors in many orders of magnitude. In this case, the spectral index should represent $p$. On the other hand, in other non-relativistic flows, we often determine $p$ from the radio spectra closer to the minimum Lorentz factor $\gamma_m$ of the electron energy distribution, where the synchrotron emission may be dominated by thermal electrons around the typical Lorentz factor rather than accelerated electrons (e.g., Park et al. 2015; Maeda 2013). Thus, GW170817 offers an opportunity to test particle acceleration theory, and continued monitoring from radio-to-X-rays is key to this end. We also note that continued X-ray observations may offer an opportunity to probe the evolution of the cooling frequency in the Newtonian limit, when $\nu_c \propto \beta^{-3} \gamma^{-2}$ (Hotokezaka et al. 2018), and thus constrain $\beta$ and the kinetic energy of the fast tail of the ejecta (see also Linial & Sari 2019).

An alternative explanation for the excess in X-rays (as compared to the radio) observed in GW170817 might be the possibility of a Compton echo of the X-rays from the prompt emission of GRB 170817A, scattering off surrounding dust (Beniamini et al. 2018). Given currently large uncertainties in the X-ray result, hereafter we focus on the constraints that the lack of a radio excess set on kilonova ejecta models.

Following Kathirgamaraju et al. (2019), the kilonova blast wave drives a shock through the interstellar medium, resulting in synchrotron emission. Electrons are accelerated to a power-law distribution of Lorentz gamma factors $\gamma > \gamma_m$, with power-law index $p$. The energy in the kilonova blast wave is distributed as $E \propto (\beta \Gamma)^{-\alpha}$, where $\beta_0$ being the minimum shock velocity. It is reasonable to assume that radio (GHz) observations are in between the minimum frequency, $\nu_m$ (corresponding to $\gamma_m$, see Nakar & Piran 2011), and the cooling frequency, $\nu_c$. In this case, the kilonova peak flux density

| Date (UT) | Epoch (days) | $\nu$ (Hz) | $F_\nu$ (\(\mu\)Jy) | $\sigma_\nu$ (\(\mu\)Jy) | Instrument | Reference |
|-----------|--------------|------------|-----------------|-----------------|------------|-----------|
| 2020 Dec 15 - 2021 Feb 08 | 1243 | $2.8 \times 10^9$ | 2.8 | 1.1-1.3 | VLA A | This work |
| 2020 Sep 19 - 2021 Feb 08 | 1199 | $3.0 \times 10^9$ | 2.86 | 0.99 | VLA A&B | This work |
| 2020 Dec 10 - 2021 Jan 27 | 1234 | $2.41 \times 10^{17}$ | $2.1 \times 10^{-4}$ | $0.7 \times 10^{-4}$ | Chandra | This work |
reads (Nakar & Piran 2011):
\[ F_{\nu, pk} \approx (1522 \text{ mJy}) \epsilon_e^{-1} \epsilon_B^{-1} n^{-2} \beta_0^{-2} E_{51}^{-2} d_{20}^{-2}, \]
where \( Q_p = Q/10^4 \) is followed for all quantities (\( Q \), all expressed in cgs units); \( \epsilon_e \) and \( \epsilon_B \) are the fractions of the total energy in the magnetic field and electrons respectively; \( n \), the number density of the medium; \( E \) is the energy of the blast wave; \( d \) is the distance to the source; the normalization constant is calculated for \( p = 2.1 \). The time at which the kilonova afterglow emission peaks can be calculated as (Kathirgamaraju et al. 2019):
\[ t_{\text{dec}} = t_{pk} \approx (3.3 \tau_t) \left( \frac{E_{\text{iso,51}}}{n^{-2}} \right)^{\frac{3}{2}} \beta_0^{-2} \left( \frac{2 + \alpha}{\beta_0 (5 + \alpha)} - 1 \right). \]

The blast wave can be approximated to be mildly relativistic before this peak, and therefore the rising part of the kilonova ejecta light curve can be easily modelled as (see Kathirgamaraju et al. 2019, and references therein):
\[ F_{\nu, \text{KN}}(t) = F_{\nu, pk} \left( \frac{t}{t_d} \right)^s, \]
where:
\[ s = \frac{3\alpha - 6(p - 1)}{8 + \alpha}. \]

In Figure 2, we plot the rising portion of the 3 GHz kilonova light curves obtained following the above prescriptions, setting \( \beta_0 = 0.3 \), \( E_{\text{iso}} = 10^{51} \text{ erg} \), \( d = 40 \text{ Mpc} \), and adopting different values for the power-law index \( \alpha \) of the energy-speed distribution of the kilonova ejecta. The solid lines correspond to the choice \( p = 2.1 \), \( \epsilon_e = 7.8 \times 10^{-3} \), \( \epsilon_B = 9.9 \times 10^{-4} \), \( n = 9.8 \times 10^{-3} \text{ cm}^{-3} \) as derived from the modeling of the earlier kilonova observations discussed in Hajela et al. (2020b). For the more generic parameters as in Kathirgamaraju et al. (2019), as evident from this Figure, to explain the absence of a kilonova detection in the radio one needs \( \alpha \gtrsim 5 \) for the case where the density and micro-physical parameters are set equal to the ones measured for the structured jet afterglow. This constraint on \( \alpha \) agrees with the predictions from numerical simulations described in Hotokezaka et al. (2018) and X-ray observations discussed in Hajela et al. (2020b). For the more generic parameters as in Kathirgamaraju et al. (2019), \( \alpha \gtrsim 20 \).

4. SUMMARY AND CONCLUSION

We have presented extensive late-time radio observations of the GW170817 field, carried out with the most extended configurations of the VLA. Combining the collected data we have built the deepest high-resolution image of the GW170817 field available so far. Our radio flux density measurements show that there is no evidence for emission in excess to the one expected from the afterglow of the GW170817 structured jet at 3 GHz and \( t \approx 1200 \text{ d} \) since merger. These results constrain the energy-speed distribution of the kilonova ejecta to be rather steep, with a power-law index of \( \alpha \gtrsim 5 \). We finally commented on how the recent detection of a potential excess in the X-rays may hint to a flattening of the power-law index of the electron energy distribution of the kilonova ejecta compared to the value of this parameter as constrained by the earlier kilonova afterglow observations. Further late-time monitoring of the GW170817 field with the VLA are likely to reveal whether a kilonova afterglow is emerging.

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