



Low-frequency View of GW170817/GRB 170817A with the Giant Metrewave Radio Telescope

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Abstract

The short gamma-ray burst (GRB) 170817A was the first GRB associated with a gravitational-wave event. Due to the exceptionally low luminosity of the prompt γ -ray and the afterglow emission, the origin of both radiation components is highly debated. The most discussed models for the burst and the afterglow include a regular GRB jet seen off-axis and the emission from the cocoon encompassing a “choked” jet. Here, we report low radio frequency observations at 610 and 1390 MHz obtained with the Giant Metrewave Radio Telescope. Our observations span a range of ~ 7 to ~ 152 days after the burst. The afterglow started to emerge at these low frequencies about 60 days after the burst. The 1390 MHz light curve barely evolved between 60 and 150 days, but its evolution is also marginally consistent with an $F_\nu \propto t^{0.8}$ rise seen in higher frequencies. We model the radio data and archival X-ray, optical, and high-frequency radio data with models of top-hat and Gaussian structured GRB jets. We performed a Markov Chain Monte Carlo analysis of the structured-jet parameter space. Though highly degenerate, useful bounds on the posterior probability distributions can be obtained. Our bounds of the viewing angle are consistent with that inferred from the gravitational-wave signal. We estimate the energy budget in prompt emission to be an order of magnitude lower than that in the afterglow blast wave.

Key words: gamma-ray burst: individual (GRB 170817A) – gravitational waves

1. Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo gravitational-wave (GW) detectors detected on 2017 August 17 for the first time the emission from two inspiraling neutron stars (GW170817; Abbott et al. 2017c). The three-dimensional localization inferred from the GW signal enabled a global network of observers to detect for the very first time electromagnetic radiation emitted during and after the neutron star inspiral.

About 1.7 s after the beginning of the neutron star inspiral, the γ -ray satellite *Fermi* detected a short gamma-ray burst GRB 170817A that also coincided spatially with GW170817 (Goldstein et al. 2017). As soon as the field became visible from the ground, optical and near-IR observations detected a new source in the credible region of GW170817, dubbed AT 2017gfo (e.g., Arcavi et al. 2017; Coulter et al. 2017; Lipunov et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; for a review see also Abbott et al. 2017b). Radio, submillimeter, and X-ray observations revealed no counterpart during the first week after GW170817 (Alexander et al. 2017; Evans et al. 2017; Hallinan et al. 2017; Kim et al. 2017; Margutti et al. 2017a). Only 9 days after GW170817, a new source at the position of AT 2017gfo emerged at X-ray frequencies

(Troja et al. 2017) and a week later also at radio frequencies (Hallinan et al. 2017).

Modeling the multiband data revealed two distinct phenomena powering the long-lasting emission from radio to X-ray frequencies. The UV-to-NIR emission up to ~ 30 days originated from the radioactive decay of lanthanides (e.g., Evans et al. 2017; Pian et al. 2017; Tanvir et al. 2017, for a critical reflection see also Waxman et al. 2018). The emission at longer and shorter wavelengths is of nonthermal origin. The brightness of this component increased since its discovery ($F_\nu \propto t^{0.8}$; Haggard et al. 2017; Hallinan et al. 2017; Margutti et al. 2017a; Mooley et al. 2017; Troja et al. 2017), while the shape of the spectral energy distribution remained constant with time ($F_\nu \propto \nu^{-0.6}$; Mooley et al. 2017). About 110 days after GW170817, long after the kilonova faded, this source also started to emerge at optical wavelengths (Lyman et al. 2018; Margutti et al. 2018).

Since GW170817 was accompanied by a short-duration GRB, the nonthermal component might naturally be connected with the GRB afterglow, but seen off-axis (Granot et al. 2017; Kim et al. 2017; Margutti et al. 2017a; Troja et al. 2017). However, Kasliwal et al. (2017), Mooley et al. (2017), and Nakar & Piran (2018) argued that the emission could be produced by the low-luminosity subrelativistic cocoon.

Table 1
Log of GMRT Observations of GRB 170817A

Date	$t - t_0$ (days)	F_ν (AG) (μ Jy)	F_ν (host) (μ Jy)	rms (μ Jy)	Beam Size (arcsec)
600 MHz					
2017 Nov 28	102.5	101 ± 26	1003 ± 23	16	5.61×5.26
2017 Dec 22	127.0	175 ± 44	973 ± 33	20	5.98×3.59
1390 MHz					
2017 Oct 23	66.6	106 ± 25	721 ± 60	19	4.41×3.05
2017 Nov 03	77.6	105 ± 24	769 ± 62	17	2.61×2.19
2017 Dec 02	106.6	109 ± 33	849 ± 83	30	3.82×2.45
2017 Dec 20	124.5	117 ± 27	851 ± 47	19	2.87×2.16
2018 Jan 16	151.5	110 ± 20	755 ± 38	14	2.83×2.15

Recently, Hotokezaka et al. (2018) proposed that the observed nonthermal emission could also be produced by the interaction of the fast tail of the neutron star ejecta with the circumstellar material.

In this paper, we present our continuing low-frequency observations of the radio transient using the Giant Metrewave Radio Telescope (GMRT), located in Pune, India (Section 2), covering the time interval from 7 to 152 days after GW170817. The transient started to emerge at 1390 MHz frequencies ~ 67 days after GW170817 and ~ 40 days later also at 610 MHz. We augment our data set with archival X-ray and radio data to model the evolution in the framework of a structured GRB jet. To characterize the highly degenerate multi-dimensional parameter space of the model, we applied the Markov Chain Monte Carlo (MCMC) technique. All uncertainties in this paper are quoted at 1σ confidence. We assume the distance to GW170817 to be 42.5 Mpc (Hjorth et al. 2017).

2. Observations and Data Reduction

2.1. GMRT Observations

We began monitoring the afterglow of GRB 170817A with the GMRT (Swarup et al. 1991) around a week after the burst (Resmi et al. 2017). The observations up to 30 days were carried out at the L band with the 32 MHz legacy correlator at 1390 MHz. These early observations yielded only upper limits (Kim et al. 2017, hereafter Paper I). We continued our observations through a series of Director’s Discretionary Time proposals (PI: Kuntal Misra), using the upgraded GMRT. On 2017 October 23, 67 days past the burst at 1390 MHz, we secured the first detection at 1390 MHz. Each of the observations took about ~ 4 hr, including overheads for calibration and slewing. A log of our observations is shown in Table 1.

2.2. Data Analysis

We processed the wideband data with the COMMON ASTRONOMY SOFTWARE APPLICATIONS (CASA¹⁴) package (McMullin et al. 2007) and the legacy system data with NRAO ASTRONOMICAL IMAGE PROCESSING SOFTWARE (AIPS¹⁵) package (Wells 1985). The data were flagged and calibrated

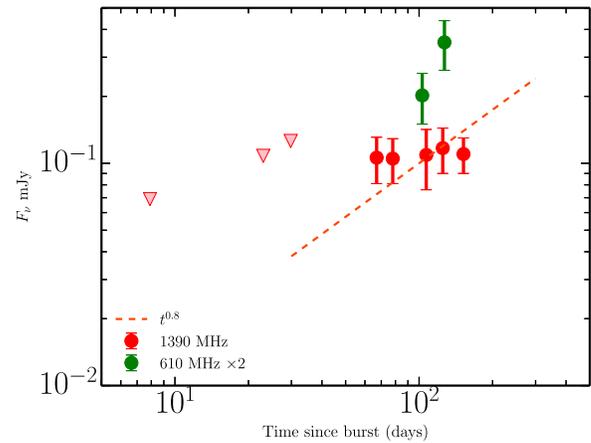


Figure 1. GMRT observations of the afterglow of GRB 170817A. The observations we report in the paper are given by solid symbols. The 610 MHz points are shifted up by a factor of two. Upper limits are displayed as downward-pointing triangles and were previously reported in Paper I. The dashed line represents a $t^{0.8}$ rise seen in higher-frequency radio data, overplotted with 1390 MHz data.

using standard procedures. The primary calibrators 3C286 or 3C147 were used as flux and bandpass calibrators, and J1248 –199 was used for phase calibration. After flux, gain, and bandpass calibration, the channel averaging was done to the extent to minimize the effect of bandwidth smearing and the target was split. On the target, we performed a few rounds of phase-only self-calibration and afterward a few rounds of amplitude and phase self-calibration.

The beam at 610 MHz has a radius of $\gtrsim 5''$ and is comparable to the distance from AT 2017gfo to the nucleus of its host galaxy.

The 610 and 1390 MHz flux was measured with a two-component Gaussian fit (for peak and underlying baseline) on the final images using JMFIT in AIPS, centered at the afterglow and the galaxy nucleus. The final error quoted is the quadrature sum of the (i) map rms, (ii) JMFIT error, and (iii) the flux scale error measured as the uncertainty in the calibrator flux. Transient and host flux measurements are summarized in Table 1.

2.3. GMRT Light Curve

Taken in isolation, the GMRT 1390 MHz light curve is consistent with a plateau phase (Figure 1). However, it is also marginally consistent with the $t^{0.8}$ rise previously derived from X-ray and high radio frequency observations (Margutti et al. 2018; Mooley et al. 2018). Our last L-band light curve extends 152 days after GW170817, while the high radio frequency observations extend to 115 days. The flatness could indeed be a slow turnover of the afterglow light curve, which was not apparent in the high radio frequency observations reported so far.¹⁶ This conclusion is also consistent with the late-time X-ray observations reported by Troja & Piro (2018b), where the *Chandra* flux at 158 days is consistent with that at 110 days since the burst.

Variabilities could also provide an explanation for the plateau phase (see Figure 1). In X-ray frequencies, the flux is also found to be variable (Troja & Piro 2018b).

¹⁴ <https://casa.nrao.edu>

¹⁵ <http://www.aips.nrao.edu>

¹⁶ This corresponds to the time of the submission of the paper. However, data released after the submission of the paper confirm the turnover.

The 610 MHz light curve is consistent with both a plateau and a $t^{0.8}$ rise. However, it spans only a duration of ~ 25 days.

2.4. Archival Data

We augment our data set with X-ray measurements reported in Margutti et al. (2018), D’Avanzo et al. (2018), and Troja & Piro (2018a); optical observations reported in Lyman et al. (2018); and radio observations reported in Mooley et al. (2018), Margutti et al. (2018), and Troja & Piro (2018a).

3. Modeling

3.1. Uniform Top-hat Jet Model

In Paper I, we used the results from the high-resolution two-dimensional relativistic hydrodynamical code BOXFIT version 2 (van Eerten et al. 2012) to interpret the multiband afterglow under the ambit of the uniform top-hat jet model. Along with the data, in that paper we presented two out of several plausible solutions: (i) a narrow jet of half-opening angle $\sim 5^\circ$ misaligned at $\sim 17^\circ$ from the observer, and (ii) a wide jet of opening angle $\sim 20^\circ$ with the jet axis 41° away from the observer line of sight.

However, recent observations indicated that the top-hat jet model is insufficient to explain the behavior of the afterglow (Margutti et al. 2018; Mooley et al. 2018). We found that the lateral expansion of the jet led to a steep decay after the peak in top-hat jet models that could fit the early data of the afterglow. We found that an $F_\nu \propto t^{0.8}$ rise lasting for about a decade in time is possible with a uniform top-hat jet. However, the parameters that lead to a $F_\nu \propto t^{0.8}$ phase between 10 and 100 days require unreasonably high values of energy and density of the ambient medium, which also lead to fluxes several orders of magnitude larger than observed. A low fraction of accelerated electrons could reduce the flux, but that results in high values of γ_m leading to the disagreement with the observed spectrum of the afterglow.

3.2. Structured-jet Model

In order to explain the evolution of the afterglow, several groups have invoked either a radial (Mooley et al. 2018) or a lateral (Lazzati et al. 2018; Lyman et al. 2018; Margutti et al. 2018) structure in the energy and velocity profile of the outflow. In the radially structured cocoon model, the relativistic jet is “choked,” and the burst and the afterglow originate from a subrelativistic cocoon (Mooley et al. 2018; Nakar & Piran 2018).

Since evidence for relativistic jets are seen in gamma-ray bursts (Frail et al. 1997; Taylor et al. 2004), we investigate the parameter space of a structured relativistic jet to explain the afterglow observations. The Gaussian structured jet we consider is similar to that previously discussed by Lazzati et al. (2018), Margutti et al. (2017b), D’Avanzo et al. (2018), Lyman et al. (2018), and Troja et al. (2018), where the kinetic energy per solid angle (\mathcal{E}) has a polar structure given by

$$\mathcal{E}(\theta) = E_c \exp\left(-\frac{\theta^2}{\theta_c^2}\right), \quad (1)$$

where θ_c is the *structure parameter* deciding the sharpness of the angular profile. A jet with a large θ_c is similar to a uniform jet. To have the same deceleration radius (r_0) across the polar

direction, we let the initial bulk Lorentz factor follow

$$\Gamma_0 \beta_0 = \Gamma_c \beta_c \exp\left(-\frac{\theta^2}{2\theta_c^2}\right), \quad (2)$$

where β is the bulk velocity of the jet normalized by the speed of light and Γ is the bulk Lorentz factor of the GRB jet. A jet where the kinetic energy is proportional to $\exp(-\theta^2)$ and the Lorentz factor is proportional to $\exp(-\theta^2/2)$ is possible if the ejected mass also follows an angular profile of $\exp(-\theta^2/2)$, which is a reasonable assumption to make.

Due to the angular structure, the initial jet Lorentz factor decreases toward high latitudes and becomes subrelativistic toward high latitudes. We assume that the initial jet Lorentz factor follows

$$\Gamma(\theta)\beta(\theta) = \Gamma_0(\theta)\beta_0(\theta)\left(\frac{r}{r_0}\right)^{-3/2}, \quad (3)$$

where $r \gg r_0$ can be considered equal to the distance from the center of the explosion. This velocity profile reduces to the Blandford–McKee self-similar solution in the ultrarelativistic limit (Blandford & McKee 1976) and the Sedov–von Neumann–Taylor solution in the nonrelativistic limit (Taylor 1950). To simplify the calculation, we assume a rigid jet that does not expand laterally.

To calculate the flux observed by an observer at an angle θ_ν from the jet axis, we follow the same formalism developed by Lamb & Kobayashi (2017). We divide the jet into N polar rings of width $\delta\theta = \theta_j/N$, which are further divided into M azimuthal elements, each with a width of $\delta\phi = 2\pi/M$. The direction to the observer’s line of sight is taken as the zero of the ϕ coordinate. An element i, k with its central axis at (θ_i, ϕ_k) from the jet axis is at an inclination $\alpha_{i,k} = \cos\theta_i \cos\theta_\nu + \sin\theta_i \sin\theta_\nu \cos\phi_k$ from the observer. As done in Lamb & Kobayashi (2017), we sum the contribution of each of these elements to obtain the total flux observed by the off-axis observer at t_{obs} at a frequency ν_{obs} . For this we interpolate the equation $t_{\text{obs}} = \frac{r}{\beta(r)c} [1 - \beta(r)\cos\alpha_{i,k}]$ and find the distance r corresponding to the t_{obs} for each jet element i, k . The off-axis flux from each element is estimated as $a^3 f_{\nu/a,i,k}^{\text{on}}(r)$, where $a = \frac{1 - \beta(r)}{1 - \beta(r)\cos\alpha_{i,k}}$ and f^{on} is the flux observed by an observer located on the central axis of the element. Again, we follow Lamb & Kobayashi (2017) to obtain $f_{\nu,i,k}^{\text{on}}$ as $\frac{L_{\nu,i,k} \Omega_{i,k}}{4\pi d_L^2 \Omega_{e,i,k}}$. Here, $\Omega_{e,i,k} = \max\left[\Omega_{i,k}, 2\pi\left(1 - \cos\frac{1}{\Gamma_{i,k}}\right)\right]$ and $\Omega_{i,k} = \int_{\phi_{k-1}}^{\phi_k} d\phi \int_{\theta_{i-1}}^{\theta_i} d\theta \sin\theta$ is the solid angle subtended by an element at a point on its central axis.

The isotropic synchrotron flux $L_\nu/4\pi d_L^2$ is estimated following Sari et al. (1998), with modifications for expressions of the downstream magnetic field, B , and minimum Lorentz factor, γ_m , of the shocked electron population, suitable for the subrelativistic flow: $B = \sqrt{32\pi m_p c^2 \epsilon_B n_0} \Gamma(\Gamma - 1)$ and $\gamma_m = 1 + \frac{m_p p - 2}{m_e p - 1} \epsilon_e (\Gamma - 1)$. Here, m_p and m_e are the proton and electron masses, respectively, c is the speed of light, p is the power-law index of the nonthermal electron population, and ϵ_e and ϵ_B are the fractional energy content in the nonthermal electron population and magnetic field, respectively. This formalism assumes a geometrically and optically thin jet. A thin shell assumption is valid because the broadband spectrum

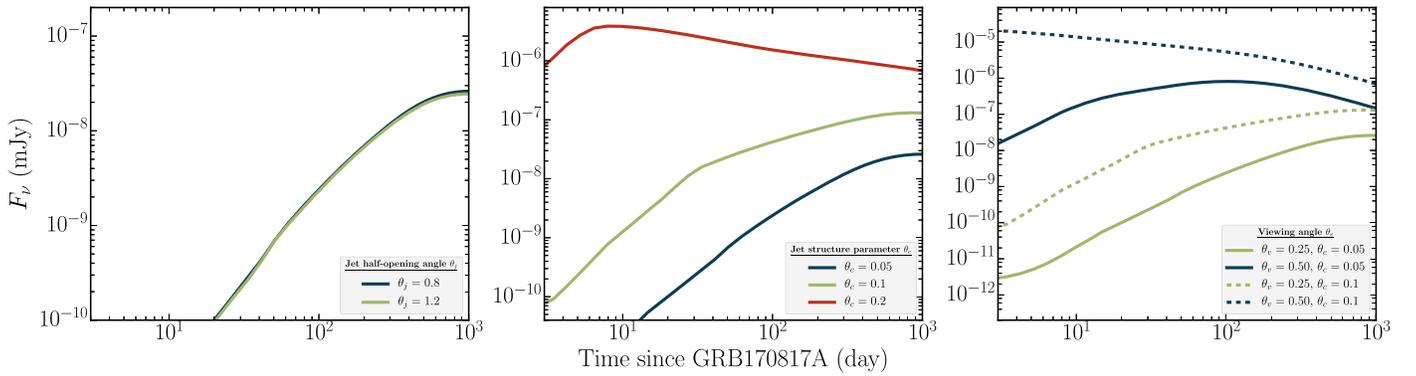


Figure 2. Sensitivity of light curves (3 keV) on the structured-jet parameters. Left: variation in the jet half-opening angle θ_j . An increase in the jet half-opening angle hardly changes the total flux. At large jet angles, the energy content in the Gaussian jet is negligible compared to the central part. For both light curves we assumed $\theta_c = 0.05$ rad and $\theta_v = 0.5$ rad. Middle: variation of jet structure parameter θ_c . The slope of the light curve before the peak is sensitive to θ_c . The peak time is determined by θ_v , and is the same for the blue and the green models. As θ_c gets larger, the light curve approaches to that of a uniform jet, and the peak shifts to earlier times. Since all curves have the same energy per solid angle ($\mathcal{E} = 5 \times 10^{51}$), an increase in θ_c leads to higher E_{tot} , which is the reason for the higher flux. For these light curves, we assumed $\theta_j = 0.8$ rad and $\theta_v = 0.5$ rad. Right: effect of viewing angle for two different θ_c values. A larger viewing angle leads to a later peak. As seen in the middle panel, the pre-peak slope is sensitive to θ_c . The rising phase of the blue dashed curve is steep, but it is out of the x -axis range.

even at MHz frequencies shows no signs of self-absorption to date.

Our model has minor differences from other structured-jet models presented in the literature. The angular profile of \mathcal{E} and $\Gamma\beta$ of D’Avanzo et al. (2018) is different from ours, but they use the same dynamical evolution for $\Gamma\beta$. Both D’Avanzo et al. (2018) and Margutti et al. (2018) use a free index (s_1 and α , respectively) to modify the angular structure. Since the afterglow parameter space is heavily degenerate with at least seven free parameters, we chose to fix the Gaussian profile. The angular profile we use is very similar to Lamb & Kobayashi (2017), except we let $\mathcal{E} \propto \exp\left(-\frac{\theta^2}{\theta_c^2}\right)$ in order to have an r_0 independent of the jet latitude. Our calculation of the jet dynamics and the equal arrival times differ from Lamb & Kobayashi (2017). They used a $t^{-3/8}$ profile for Γ and scaled the observed time by the Doppler factor (a) to obtain the equal arrival times. Since β can be considerably lower than unity at high jet latitudes, we chose to do an interpolation to obtain the equal arrival time surfaces.

3.3. Model Parameters and the Shape of the Light Curve

The structured jet can be specified with four parameters, E_c , Γ_c , θ_c , and θ_j . The first three parameters were mentioned in the previous section. The last parameter, θ_j , corresponds to the half-opening angle if there is a hard edge of the jet beyond which the energy sharply drops down.

Similar to top-hat models, Γ_c influences the deceleration time of the jet, and E_c influences both the deceleration time as well as the overall level of flux. Hence, we concentrate here on the jet profile θ_c and the jet half-opening angle θ_j . In addition, the observer’s viewing angle θ_v also modifies the light curve. Figure 2 shows a diverse assembly of light curves for different values of θ_j , θ_c , and θ_v .

The half-opening angle θ_j is the least sensitive of all. The jet structure parameter θ_c plays a crucial role in the rise time and the slope of the light curve. In addition, along with θ_v , θ_c also influences the peak time. A small θ_c corresponds to a sharply varying profile, where the jet core is far more energetic than its edges, whereas a large θ_c broadly resembles a uniform jet.

Table 2
Prior and Posterior Distributions of the Structured-jet Afterglow Model

Parameter	Prior Range	Posterior
$\log(E_c/\text{erg})$	47 – 54	$51.76^{+0.52}_{-0.39}$
Γ_c	30 – 300	$215.4^{+60.3}_{-85.9}$
θ_c (rad)	0.07 – 0.2	$0.12^{+0.04}_{-0.03}$
θ_v (rad)	0.1 – 0.9	$0.47^{+0.15}_{-0.08}$
$\log(n_0/\text{cm}^{-3})$	–5 – 2	$-2.68^{+0.88}_{-1.00}$
$\log \epsilon_B$	–5 – 0.5	$-4.37^{+1.10}_{-0.48}$
$\log \epsilon_e$	–2 – 0.5	$-0.66^{+0.13}_{-0.45}$

Note. We chose a uniform distribution for each prior. The values of the marginalized posterior distributions represent the median of the corresponding 16th and 84th percentiles.

3.4. Parameter Estimation

The parameter space of our afterglow model is nine-dimensional, $\Theta = E_c, \Gamma_c, \theta_c, \theta_j, \theta_v, n_0, \epsilon_B, \epsilon_e, p$. To reduce the number of free parameters, we make two additional assumptions. First, the spectral energy distribution from X-ray to radio frequencies is well described by a simple power law. Following Margutti et al. (2018), we fix the value to $p = 2.17$. Second, it is natural to let the profile go toward a polar angle of $\pi/2$. Moreover, we found that the light curves are not very sensitive to the value of θ_j (left panel of Figure 2). No bounds on θ_j could be obtained from our initial MCMC analysis either. Therefore, we fixed $\theta_j = 1.2$ rad in our final analysis. We chose a value less than $\pi/2$ to avoid numerical errors in the synchrotron flux calculation that result from extremely low values of jet velocity β . We thus reduced the number of free fitting parameters to seven.

We used the publicly available affine invariant MCMC parameter estimation code EMCEE version 2.2.1 (Foreman-Mackey et al. 2013) to obtain the bounds of the parameters consistent with the data. We chose a uniform distribution for the prior of each parameter with the ranges displayed in Table 2 and generated 1.5×10^6 realizations of the model (500 walkers and 3000 steps). Our results are presented in Figure 3. To check for convergence, we repeated the simulation multiple times with different initial values of the walkers.

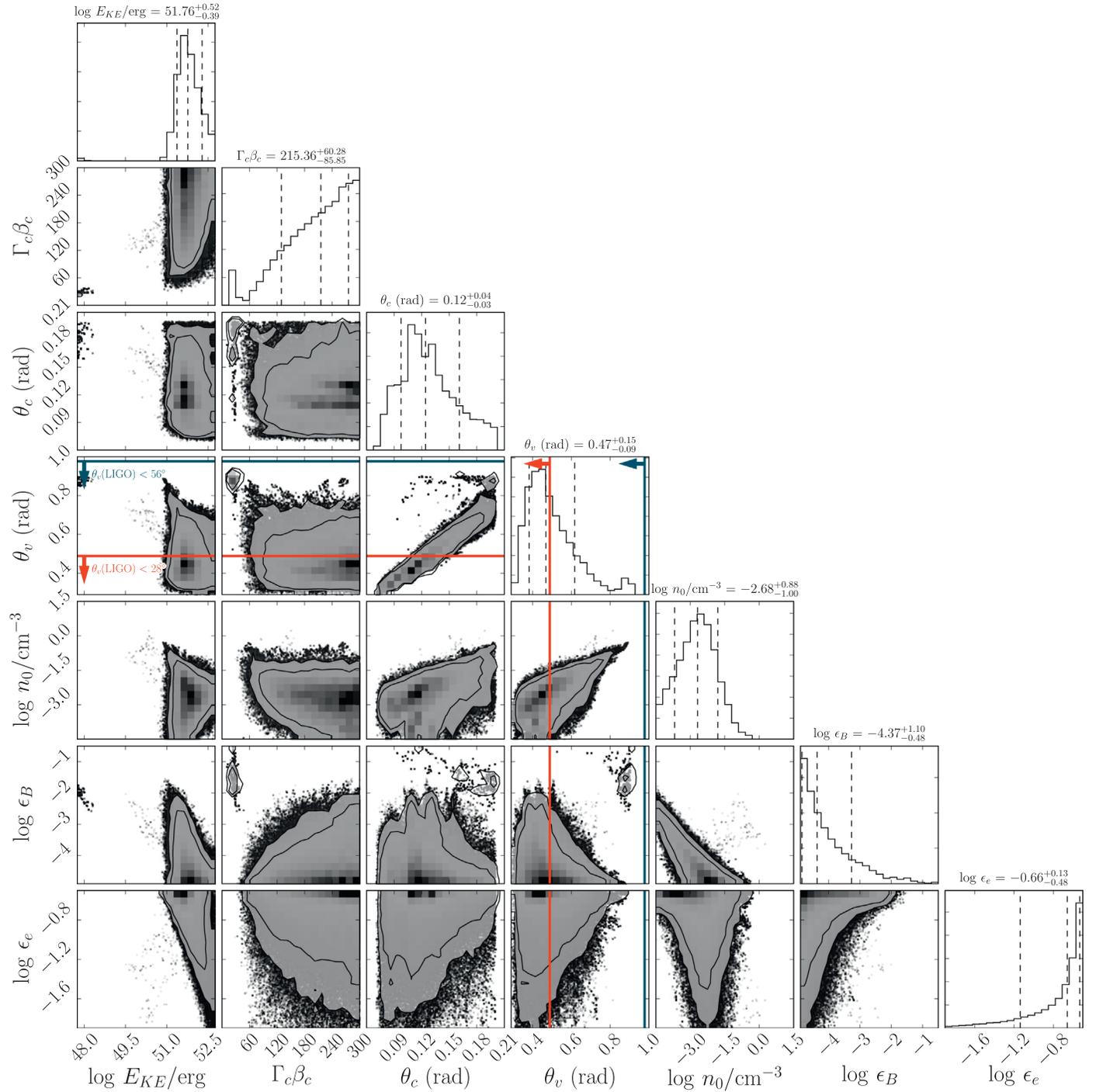


Figure 3. Posterior distributions and degeneracies of the model parameters, after removing the burn-in phase. The median values and their 1σ uncertainties are displayed on top of the marginalized distributions. The blue and red lines display the constraints from the GW signal (Abbott et al. 2017c). The tighter constraint of $\theta_v < 28^\circ$ was derived using a distance of 42.5 Mpc toward NGC4993, the host of GRB 170817A.

Here, we have only considered observations that were available at the time of the submission of the paper, i.e., up to 158.5 days. After submission, later epoch data were released (D’Avanzo et al. 2018; Dobie et al. 2018). These show the decline of the radio and X-ray light curves. We restrict our analysis to the rising phase of the afterglow in this paper. In a future paper releasing the next set of GMRT observations, we plan to use the newer data along with a more detailed modeling.

Though the parameter space is degenerate and the data are not highly constraining (Margutti et al. 2018), we could obtain tight bounds on E_c , n_0 , θ_c , and θ_v . Sixteen percent and 84% quantiles of the posterior correspond to $2 \times 10^{51} < E_c < 2 \times 10^{52}$. Total energy E_{tot} in the jet is given by $\int_0^{2\pi} d\phi \int_0^{\theta_j} d\theta \mathcal{E} \sin \theta$, which leads to

$$E_{\text{tot}} = \pi E_c \theta_c^2 \left\{ 1 - \exp\left(-\frac{\theta_j^2}{\theta_c^2}\right) \right\}. \quad (4)$$

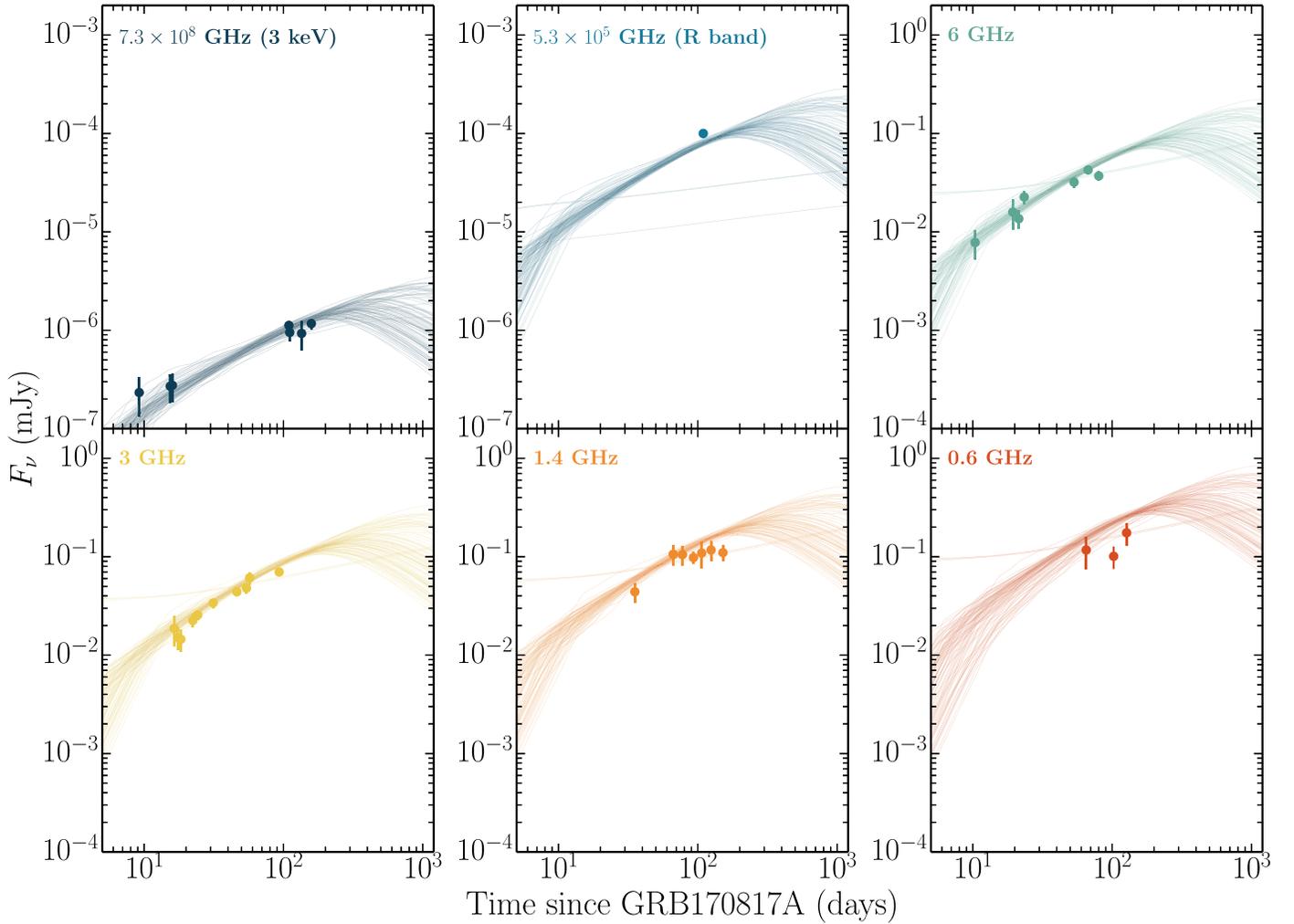


Figure 4. 610 and 1390 MHz GMRT light curves along with higher-frequency data from the literature (detections: circles; upper limits: triangles). Overlaid are 100 random realizations from the posterior chain from the run where energy fractions are restricted to be <0.3 (Figure 3). Some light curves show small-scale undulations, due to the limited resolution in polar directions. Since the data are dominated by higher radio frequencies, the flatness of the GMRT 1390 MHz light curve is not well reproduced in the model realizations.

Corresponding to the mean of the distribution of θ_c and E_c , $E_{\text{tot}} = 2.6 \times 10^{50}$ ergs. The ambient number density, $n_0 \sim 10^{-2} - 10^{-4} \text{ cm}^{-3}$, is consistent with what is expected for short GRB environments (Fong et al. 2015). Our bounds on θ_v are consistent with that from the GW analysis from LIGO/Virgo (Abbott et al. 2017c). We find that a fairly low fraction ($<10^{-4}$) of thermal energy density is deposited in the magnetic field, but the fraction going to electrons is toward the maximum possible limit. We notice a tight constraint between θ_c and θ_v . This comes from the rising slope of the afterglow being tightly constrained by high radio frequencies, as expected from the behavior of the light curves seen in Figure 2. The bulk Lorentz factor is sensitive only to the rise time of afterglow, and hence is not constrained well.

Our bounds on θ_v (27_{-5}^{+5} degrees) are within the broad bounds of the LIGO analysis (Abbott et al. 2017d). The combined LIGO and DES-SHoES bounds presented in Abbott et al. (2017a) are consistent with our posterior. However, the LIGO DES-SHoES bounds along with our posterior will tightly constrain the value of θ_v between 20° and 33° . The best fit values of θ_v and ϵ_e of

Lazzati et al. (2018) are within our posterior bounds, but their n_0 is relatively low, where our bounds are at a higher range, and their ϵ_B is relatively higher than ours. Our posterior is very similar to that of Troja et al. (2018). We have slightly tighter bounds on \mathcal{E} , θ_c , θ_v , and n_0 . Troja et al. (2018) also vary θ_j and p , which we keep fixed. Our bounds on ϵ_B are broader than theirs and also go down to lower values. The structured-jet parameters that D’Avanzo et al. (2018) and Lyman et al. (2018) have used for the light curves they present are well within our posterior bounds.

In Figure 4, we present 100 random realizations drawn from the posterior distribution. The higher radio frequencies dominate the data, and hence the flatness in GMRT 1390 MHz is not reproduced well by the models. Late observations at higher frequencies may agree with the flatness in the GMRT L-band light curve and may refine these predictions.

We have restricted the upper bounds of the prior distributions of the microphysical parameters ϵ_e and ϵ_B to 0.3 (Table 2), allowing at most one-third of the shock generated thermal energy each in the magnetic field and in the nonthermal electrons. However, since the posterior of ϵ_e shows a preference

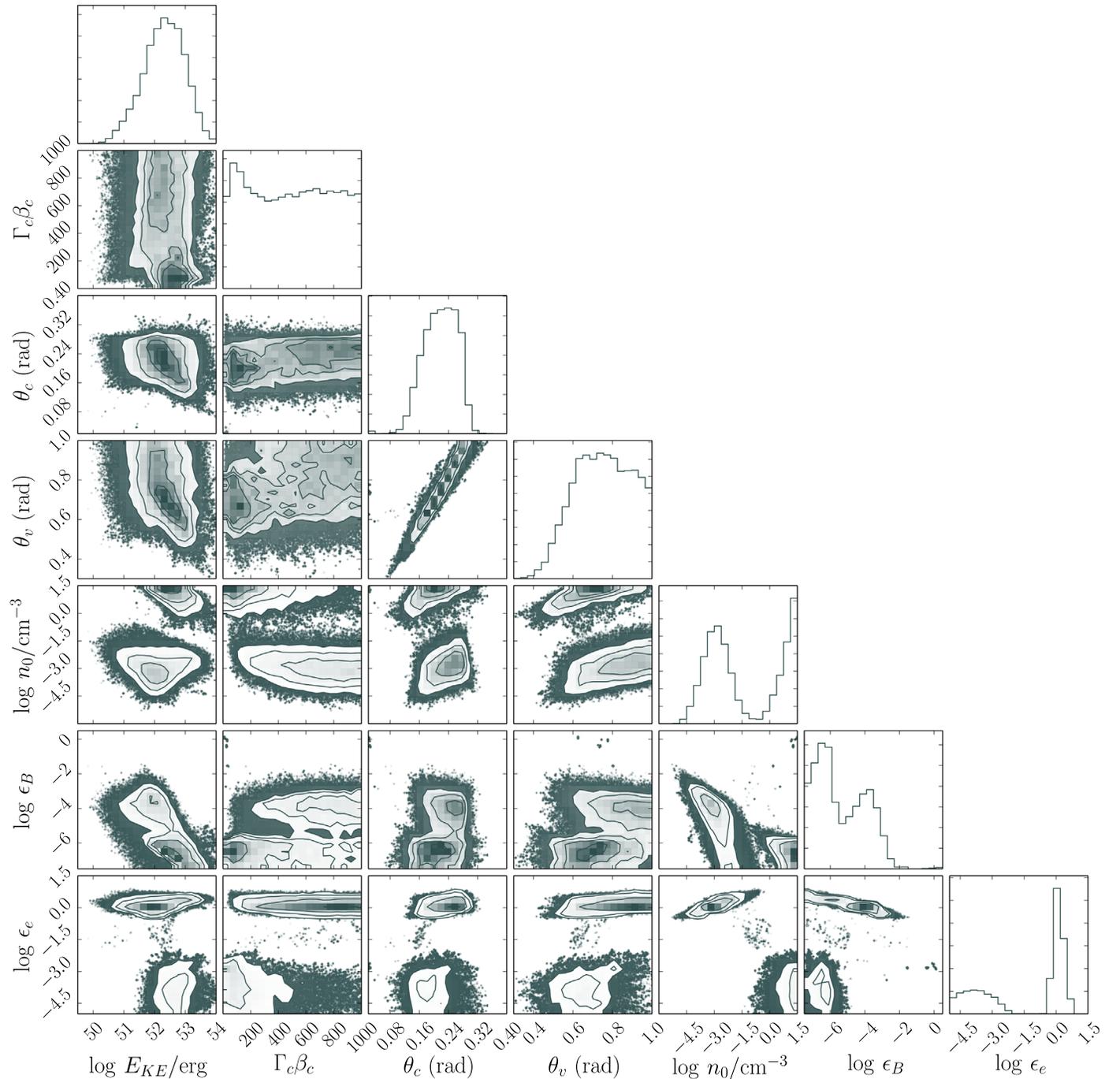


Figure 5. Posterior distribution for the MCMC run where the prior ranges of the microphysical parameters were not restricted to be below unity. Posterior of θ_v and n_0 has also changed considerably from Figure 3. Bimodal distributions appear in n_0 , ϵ_B , and ϵ_e . Likelihood peaks at unphysical or unrealistic values for microphysical parameters. Additional elements in the model, or more data, or both may be required to constrain the posterior better. Such an analysis is beyond the scope of this paper, and we postpone it for future work.

toward higher values, we ran a test simulation by extending the prior distribution to unphysical values ($\epsilon_{e,B} > 1$). The resultant posterior of ϵ_e peaks at a relatively high value of 0.9, and the 84% quantile extends to an unphysical value of 1.9. In addition, extending the priors of ϵ_e and ϵ_B demanded extending the parameter spaces of θ_v and n_0 as well. The resultant posterior of θ_v is very different from the case where $\epsilon_{e,B} < 0.3$ and is not in agreement with the LIGO/Virgo limit of $\theta_v < 28^\circ$. Posteriors of two other parameters, n_0 and ϵ_B , also change remarkably in this case to clear multimodal distributions. The posterior of

ϵ_B peaks at a fairly low 10^{-7} . We present the final posterior distribution in Figure 5 and Table 3. For further analysis we do not consider this run, as it favors unphysical ranges of microphysical parameters and values of θ_v above the LIGO/Virgo limit. However, this behavior of the posterior may be a hint of additional elements required in the afterglow model. On the other hand, it also may be an indication that the amount of data is still too small to accurately constrain the model parameters. A more detailed analysis will be presented in a forthcoming paper releasing our next set of data.

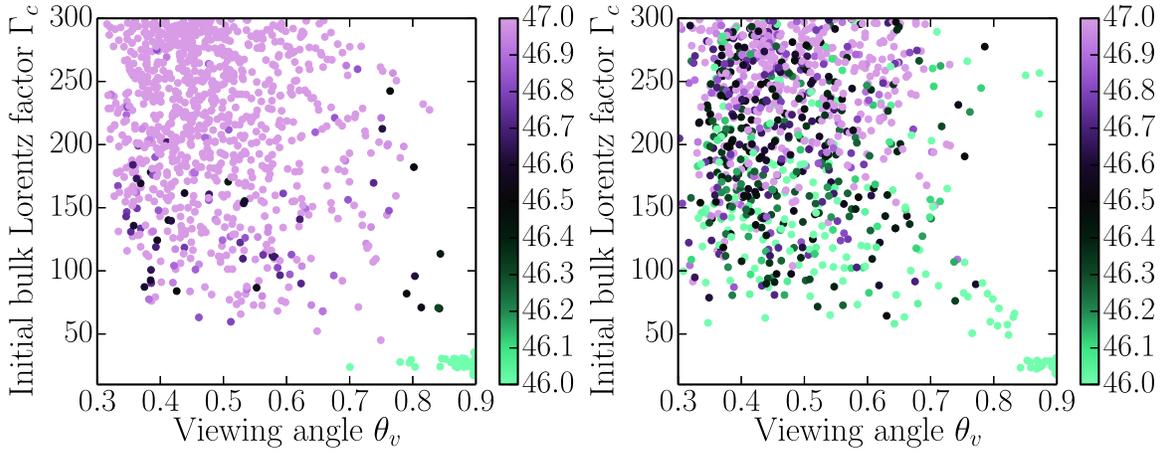


Figure 6. E_{iso}^γ reproduced by 5000 random realizations of the afterglow solutions. The points are color-coded with the numerically estimated value of E_{iso}^γ . While the afterglow solutions have four parameters relevant to the prompt emission (E_c , θ_c , θ_v , Γ_c), we have only shown two dimensions (Γ_c and θ_v) here. The anti-correlation, i.e., a higher Γ_c requires a lower θ_v to be able to reproduce a given E_{iso}^γ and vice versa, is obvious in the figure. The Fermi observed $E_{\text{iso}}^\gamma = (3.08 \pm 0.72) \times 10^{46}$ erg (Goldstein et al. 2017) (between 46.4 and 46.6 in log-scale). The left panel is for $\zeta = 1$ and the right panel is for $\zeta = 0.1$. A highly relativistic structured outflow can well describe both the prompt and afterglow observations. Nevertheless, the prompt emission seems to have carried a relatively lower amount of energy than the afterglow.

Table 3
Posterior Distributions for the Unrestricted ϵ_e Prior

Parameter	Posterior
$\log(E_c/\text{erg})$	$52.33_{-0.70}^{+0.64}$
Γ_c	$493.6_{-353.5}^{+343.4}$
θ_c (rad)	$0.22_{-0.05}^{+0.05}$
θ_v (rad)	$0.75_{-0.15}^{+0.16}$
$\log(n_0/\text{cm}^{-3})$	$-2.27_{-1.11}^{+3.40}$
$\log \epsilon_B$	$-5.77_{-1.07}^{+2.08}$
$\log \epsilon_e$	$-0.09_{-3.86}^{+0.37}$

Note. We chose a uniform distribution for each prior. The values of the marginalized posterior distributions represent the median of the corresponding 16th and 84th percentiles.

4. Constraints from Prompt Emission

In the off-axis structured-jet scenario, the properties of the observed prompt emission, particularly the isotropic equivalent energy (E_{iso}^γ), is sensitive to the jet bulk Lorentz factor (Γ_c), jet structure parameter (θ_c), and viewing angle (θ_v) (Yamazaki et al. 2003; Donaghy 2006). Assuming that the burst and the afterglow are produced by an off-axis relativistic jet, further constraints on Γ_c , θ_c , and θ_v can be arrived at in conjunction with the afterglow parameter space. We have carried out the same analysis in Paper I for the uniform top-hat jet. Here, we extend it to the Gaussian structured jet.

The observed GRB flux, from which the E_{iso}^γ is derived, is the intensity integrated over the surface of the jet visible to the observer. The flux depends on the viewing angle θ_v , the energy content of the jet, and the bulk Lorentz factor. In order to obtain E_{iso}^γ , we follow the framework developed by Salafia et al. (2015). They derive that the isotropic equivalent energy in prompt emission observed by an off-axis observer is

$$E_{\text{iso}}^\gamma(\theta_v) = \int d\Omega \frac{\delta^3(\alpha)}{\Gamma(\theta)} u^\gamma(\theta), \quad (5)$$

where $\delta(\alpha)$ is the Doppler factor given by $1/\Gamma(1 - \beta \cos \alpha)$ and $u^\gamma(\theta)$ is the energy per solid angle in prompt emission. The

angle α entering in the expression of δ is the same as defined in Section 3.2, the angle between the observer line of sight and the normal to jet surface at θ, ϕ .

We consider $u^\gamma(\theta)$ to follow the same functional dependence as \mathcal{E} , the energy per solid angle in the afterglow blast wave (Equation (1)):

$$u^\gamma(\theta) = u_c \exp\left(-\frac{\theta^2}{\theta_c^2}\right). \quad (6)$$

In order to obtain the normalization u_c , which gives the energy per solid angle at the jet axis ($\theta = 0$), we assume that the kinetic energy budget in the afterglow, E_{tot} , given in Equation (4), and the total energy radiated away in prompt emission as measured by an on-axis observer are related by a factor of ζ . This assumption is motivated by a constant γ -ray efficiency (Cenko et al. 2011) seen in long GRBs detected by γ -ray triggers, where the observer is very likely to be aligned close to the axis of the jet.

Total isotropic equivalent energy in prompt emission as measured by an on-axis observer is $E_{\text{iso}}^\gamma(\theta_v = 0)$. Therefore, to obtain u_c ,

$$u_c \int_0^{\theta_j} d\Omega \exp\left(-\frac{\theta^2}{\theta_c^2}\right) \frac{\delta^3(\theta_v = 0)}{\Gamma(\theta)} = \zeta \frac{E_{\text{tot}}}{(1 - \cos \theta_j)}. \quad (7)$$

The factor $(1 - \cos \theta_j)$ converts the afterglow energy E_{tot} to isotropic equivalent energy.

We consider 5000 random realizations of the the posterior chain and see whether a given realization can reproduce the observed E_{iso}^γ (Goldstein et al. 2017) with reasonable values of ζ . From Cenko et al. (2011), a variation in ζ from 0.05 to 40 is commonly seen, with a mean value being ~ 4 .

For the given realization, we first obtain u_c using Equation (7) after replacing θ_v by 0 and then proceed to obtain $E_{\text{iso}}^\gamma(\theta_v)$ using Equation (5). In Figure 6, we display our results for $\zeta = 1$ and $\zeta = 0.1$. We find that the observed Fermi E_{iso}^γ can be reproduced for a good fraction of the posterior if the energy budget in prompt emission is of an order of magnitude lower than that in the afterglow. For $\zeta = 1$, i.e., similar

energies in the afterglow and prompt emission (i.e., for 50% γ -ray efficiency), only a few low bulk Lorentz factor solutions can reproduce the observed E_{iso}^{γ} . However, a $\zeta \sim 0.1$ is not unusual of ordinary GRBs (Cenko et al. 2011) and is also supportive of a low efficiency process like internal shocks. This analysis shows that a relativistic structured outflow is successful in describing both the prompt and the afterglow observations of GRB 170817A, albeit the posterior distribution of ϵ_e currently prefers extremely high values.

5. Summary

We present the low radio frequency observations of the afterglow of GRB 170817A/GW170817 with the GMRT. We began detecting the afterglow at 1390 MHz starting from ~ 65 days after the burst and are continuing to follow it up in low radio frequencies. We present 1390 MHz observations up to 152 days after burst. The light curve is particularly flat, which may indicate a slow turnover in the flux evolution.¹⁷

We interpreted the multiwavelength afterglow in the framework of a structured jet with a Gaussian velocity and energy profile. Bounds on the jet energy, angular structure, observer's viewing angle, and ambient density are obtained through an MCMC parameter estimation. The energy per solid angle at the jet axis is $5.8_{-3.4}^{+13.3} \times 10^{51}$ erg, θ_c is $6.9_{-1.5}^{+2.3}$ deg, θ_v is 27_{-5}^{+8} deg, and ambient density is $0.002_{-0.002}^{+0.014}$ cm⁻³. While the initial bulk Lorentz factor could not be well constrained, a relativistic flow with Γ of a few hundred close to the jet axis is perfectly acceptable. These parameters are consistent with that of typical short-duration GRBs. We find that isotropic energy observed in the prompt emission can be reproduced if the total energy budget in the prompt emission is an order of magnitude lower than that in the afterglow. Such a difference in energy content is not unusual for GRBs. Our analysis supports the view that GRB 170817A is similar to standard GRBs, with typical energetics and bulk Lorentz factors, except that it is viewed at an angle less probable for γ -ray triggered events. Seen at such extreme angles, the presence of an angular structure in the outflow has become evident in the case of GRB 170817A.

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high-performance (HPC) and throughput (HTC) computing infrastructure.

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¹⁷ This claim is supported by later observations published while the paper was in revision (Dobie et al. 2018).

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