GRB 170817A Afterglow from a Relativistic Electron–Positron Pair Wind Observed Off-axis

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Abstract

A relativistic electron–positron (e$^-$$^+$) pair wind from a rapidly rotating, strongly magnetized neutron star (NS) would interact with a gamma-ray burst (GRB) external shock and reshape afterglow emission signatures. Assuming that the merger remnant of GW170817 is a long-lived NS, we show that a relativistic e$^-$$^+$ pair wind model with a simple top-hat jet viewed off-axis can reproduce multiwavelength afterglow lightcurves and superluminal motion of GRB 170817A. The Markov Chain Monte Carlo (MCMC) method is adopted to obtain the best-fitting parameters, which give the jet half-opening angle $\theta_j \approx 0.12$ rad and the viewing angle $\theta_v \approx 0.23$ rad. The best-fitting value of $\theta_v$ is close to the lower limit of the prior that is chosen based on the gravitational-wave and electromagnetic observations. In addition, we also derive the initial Lorentz factor $\Gamma_0 \approx 49$ and the isotropic kinetic energy $E_{K,iso} \approx 1 \times 10^{52}$ erg. Consistency between the corrected on-axis values for GRB 170817A and typical values observed for short GRBs indicates that our model can also reproduce the prompt emission of GRB 170817A. An NS with a magnetic field strength $B_p \approx 1.6 \times 10^{13}$ G is obtained in our fitting, indicating that a relatively low thermalization efficiency $\eta \lesssim 10^{-3}$ is needed to satisfy observational constraints on the kilonova. Furthermore, our model is able to reproduce a late-time shallow decay in the X-ray lightcurve, and predicts that the X-ray and radio flux will continue to decline in the coming years. 

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Neutron stars (1108)

1. Introduction

On 2017 August 17 at 12:41:04 UTC, the Advanced Laser Interferometer Gravitational-Wave Observatory and Advanced Virgo Interferometer gravitational-wave detectors detected the first gravitational-wave (GW) event GW170817 from a binary neutron star (BNS) merger (Abbott et al. 2017a). About 1.7 s after the coalescence, the Fermi Gamma-ray Burst Monitor and the International Gamma-Ray Astrophysics Laboratory were independently triggered by a low-luminosity short gamma-ray burst (sGRB) GRB 170817A (Abbott et al. 2017b; Goldstein et al. 2017; Savchenko et al. 2017). The detection of GRB 170817A confirmed that at least some sGRBs are associated with BNS merger events. Roughly 11 hr later, an optical counterpart AT2017gfo was discovered in the galaxy NGC 4993 (Coulter et al. 2017). Counterparts at ultraviolet and infrared bands were also detected within one day (Soares-Santos et al. 2017). These observations support the hypothesis that AT2017gfo is a kilonova powered by the radioactive decay of rapid neutron-capture process nuclei synthesized within the ejecta (Kasen et al. 2017; Pian et al. 2017). About 9 days later, Chandra X-ray Observatory detected X-ray emission at the position of AT2017gfo (Troja et al. 2017). About 16 days after the merger, a radio band counterpart was detected (Hallinan et al. 2017). The X-ray and radio emission can be characterized by a nonthermal power-law spectrum, which is consistent with the GRB afterglow from a relativistic shock. The gravitational-wave signal, combined with the following electromagnetic counterparts, helps to understand the process of a BNS merger and possible products, showing a breakthrough for multimessenger astronomy.

Continued follow-up observations reveal that the luminosity of a multiwavelength afterglow gradually increased, peaked around 160 days after the merger, then started rapidly decreasing (Margutti et al. 2018; Mooley et al. 2018a; Ruan et al. 2018; Makhathini et al. 2020; Troja et al. 2020). The multiwavelength behavior from radio to X-rays is different from a typical GRB afterglow. Considering the low luminosity of the prompt emission, the explanations for the afterglow luminosity evolution usually fall into two types. The first explanation invokes a structured jet, which has an angular distribution in energy and Lorentz factor. The GRB 170817A afterglow is consistent with the emission from a structured jet viewed off-axis (Abbott et al. 2017c; Troja et al. 2017, 2018, 2019; Lazzati et al. 2018; Lyman et al. 2018; Margutti et al. 2018; Mooley et al. 2018b; Hajela et al. 2019; Lamb et al. 2019). The second explanation is based on a classical top-hat jet model while considering additional continuous energy injection into a jet (e.g., Geng et al. 2018; Li et al. 2018; Lamb et al. 2020).

However, the central remnant of GW170817, which depends on the neutron star (NS) equation of state (EoS), remains a question. Depending on whether the NS EoS is stiff enough, the remnant could be a black hole, a temporal hypermassive NS, or a long-lived massive NS. Although there are theories against a long-lived massive NS as the merger remnant (e.g., Granot et al. 2017; Margalit & Metzger 2017; Ciolfi 2020), there is no direct evidence that rules out the possibility that the post-merger remnant is a stable NS. A relativistic jet could also be launched through $\nu\bar{\nu}$ annihilation in a neutrino-dominated accretion flow (NDAF) mechanism from such a stable NS with a hyperaccreting accretion disk (Zhang & Dai 2008, 2009, 2010). In addition, the existence of an NS remnant can reduce the requirement on the ejecta mass in the kilonova model due to an additional energy injection from the NS (Li et al. 2018; Metzger et al. 2018; Yu et al. 2018). If the remnant is a long-lived massive NS, it is suggested that a Poynting-flux-dominated
outflow would flow out from the NS. This outflow can be accelerated due to magnetic dissipation (e.g., reconnection), and eventually be dominated by the energy flux of an ultrarelativistic wind that consists of electron–positron ($e^+e^-$) pairs (Coroniti 1990; Michel 1994; Kirk & Skjæraasen 2003). Dai (2004) realized that the continuous ultrarelativistic $e^+e^-$ pair wind would interact with the GRB external shock and reshape the afterglow emission signatures. Yu & Dai (2007) used this model to explain the shallow decay phase of the early GRB X-ray afterglows. Geng et al. (2018) modeled the first 150 days of GRB 170817A afterglow lightcurves in this scenario. However, some new observational facts have been updated since then. Soon afterwards, Mooley et al. (2018c) reported the radio observations of GRB 170817A afterglow using a Very Long Baseline Interferometry (VLBI) and found that the radio source showed superluminal apparent motion between 75 days and 230 days after the merger event. A mean apparent velocity of the radio source along the plane of the sky $v_{\text{app}} = (4.1 \pm 0.5)c$ was measured. Recently, the Chandra X-ray Observatory continuously detected X-ray emission from the location of GRB 170817A (Hajela et al. 2020a, 2020b, 2021a, 2021b), which extended the afterglow data to about 3.3 yr after the merger. The late-time derived unabsorbed X-ray flux is higher than what is expected from the structured jet model (Hajela et al. 2020b, 2021a, 2021b; Makhathini et al. 2020; Troja et al. 2020). However, the late-time relativistic radio observations did not show this excess (Balasubramanian et al. 2021; Hajela et al. 2021b). Therefore, it is necessary to revisit an off-axis afterglow from an $e^+e^-$ pair wind scenario supposing that the remnant of GW170817 is a long-lived massive NS.

This paper is organized as follows. In Section 2.1 we give the details of our numerical afterglow model from an $e^+e^-$ pair wind scenario. In Section 2.2 we describe the methods of fitting the data from GRB 170817A with our model. Our fitting data includes the thousand-day multiwavelength afterglow and the VLBI proper motion. In Section 3 we describe our results. Our discussion and conclusions can be found in Section 4. The luminosity distance of GRB 170817A DL = 41 Mpc (Hjorth et al. 2017; Cantiello et al. 2018) is adopted in this paper.

2. Method

2.1. The Relativistic $e^+e^-$ Pair Wind Model

We assume that the central remnant of GW170817 is a long-lived NS. A Poynting-flux-dominated outflow is launched from the NS, whose wind luminosity is dominated by the magnetic dipole spin-down luminosity, i.e., (Shapiro & Teukolsky 1983)

$$L_w = \frac{B_p^2 R_s^6 \Omega^4}{6c^3} \sim 9.64 \times 10^{44} B_{p,13}^2 P_{0,-9}^{-4} R_{s,6}^6 \times \left(1 + \frac{t_{\text{obs}}}{\tau_{\text{sd}}}\right)^{-2} \text{erg s}^{-1},$$

(1)

where $B_p = 10^{13} B_{p,13}$ G, $P_0 = 10^{-3} P_{0,-3}$ s, and $R_s = 10^6 R_{s,6}$ cm are the polar surface magnetic field strength, radius, and initial spin period of NS, respectively. $t_{\text{obs}}$ is the time measured in the observer frame. $\tau_{\text{sd}} = 2.05 \times 10^4 I_{45} R_{s,6}^{-2} P_{0,-9}^{-3} c$ s is the characteristic spin-down timescale, where $I = 10^{45} I_{45}$ g cm$^2$ is the moment of inertia of the NS. For simplicity, $P_{0,-3}$, $R_{s,6}$, and $I_{45}$ are taken to be unity throughout this work.

As it propagates outwards, the Poynting-flux-dominated outflow can be dissipated and accelerated by magnetic reconnection, which is eventually dominated by an ultrarelativistic wind consisting of $e^+e^-$ pairs with bulk Lorentz factor $\Gamma_w \sim 10^4 - 10^7$ (Atoyan 1999). Here we adopt $\Gamma_w = 10^4$ as a fiducial value in our calculations. Based on the luminosity $L_w$ and the bulk Lorentz factor $\Gamma_w$ of the $e^+e^-$ pair wind, and the assumption that the $e^+e^-$ pair wind is isotropic, the comoving electron number density can be estimated as

$$n_w' \sim \frac{L_w}{4\pi R^2 \Gamma_w^2 m_e c^3},$$

(2)

where $m_e$ is the mass of an electron, $c$ is the speed of light, and $R$ is the distance from the central engine.

As shown in Figure 1, most of the wind energy is injected into the kilonova ejecta, and only a small fraction of the $e^+e^-$ pair wind ($(1 - \cos \theta_j)/2$, where $\theta_j$ is the half-opening angle of the jet) propagates outside the ejecta in the jet direction. When the ultrarelativistic $e^+e^-$ pair wind interacts with its surrounding medium, a pair of shocks will develop: a forward shock (FS) that propagates into the medium, and a reverse shock (RS) that propagates into the wind. Before this interaction, a forward shock has formed when the GRB jet interacts with the medium. For simplicity, we assume that the two forward shocks eventually merged into one forward shock. Thus, there are four regions separated by two shocks: (1) the unshocked medium, (2) the shocked jet and medium, (3) the shocked wind, and (4) the unshocked wind (Dai 2004). Regions 2 and 3 are separated by the contact discontinuity.

We solve a set of differential equations that describe the dynamics of such an FS-RS system and consider both synchrotron radiation and inverse Compton (IC) radiation from shock-accelerated electrons. The details of calculating the multiwavelength lightcurves can be seen in Appendix A.
2.2. Modeling the GRB 170817A Afterglow

A numerical model is established to fit the GRB 170817A afterglow data, including the multiwavelength afterglow and the VLBI proper motion. The multiwavelength afterglow data are taken from the following literature: Makhathini et al. (2020) collected and reprocessed the available radio, optical, and X-ray data spanning from 0.5 days to 1231 days after the merger; Troja et al. (2021) updated the 0.3–10 keV X-ray data to 3.3 yr after the merger. Our fitting data include the following specific bands: frequencies at 3 GHz and 6 GHz from Karl G. Jansky Very Large Array (VLA), wavelength at 600 nm from the Hubble Space Telescope (HST) F606W, energy at 1 keV from the Chandra X-ray Observatory and the XMM-Newton Observatory, and energy at 0.3–10 keV from the Chandra X-ray Observatory, which can be regarded as representative of the multiwavelength afterglow, as shown in Figure 2. In order to fit the VLBI proper motion, we develop a method used to calculate the proper motion of the flux centroid, which can be seen in Appendix B. As part of fitting data, we construct a data

![Figure 2. Relativistic $e^+e^-$ pair wind model fit to the multiwavelength afterglow lightcurves of GRB 170817A. The dashed and dotted curves represent the emission from the FS and RS, respectively. The solid curves are the total emission lightcurves.](image)

point based on the mean apparent velocity of the source, as shown in Figure 3.

We develop a Fortran-based numerical model and implement the Markov Chain Monte Carlo (MCMC) techniques by using the emcee Python package (Foreman-Mackey et al. 2013). FZPY is employed to provide a connection between Python and Fortran languages. We perform the MCMC with 22 walkers for running at least 100,000 steps, until the step is longer than 50 times the integrated autocorrelation time $\tau_{ac}$, i.e., $N_{\text{step}} = \max(10^5, 50\tau_{ac})$ to make sure that the fitting is sufficiently converged (Foreman-Mackey et al. 2013). Once the MCMC is done, the best-fitting values and the 1σ uncertainties are computed as the 50th, 16th, and 84th percentiles of the posterior samples.

The free parameters in the fitting include the half-opening angle of the jet ($\theta_{j}$), the viewing angle ($\theta_v$), the NS surface magnetic field strength at the polar cap region ($B_p$), the isotropic kinetic energy of the jet after prompt emission ($E_{K,\text{iso}}$), the initial Lorentz factor of the jet after prompt emission ($\Gamma_0$), the number density of the medium ($n_1$), the field strength at the polar cap region ($B_{p}$), the fraction of the shock internal energy that is partitioned to magnetic fields in regions 2 ($\epsilon_{B,2}$) and 3 ($\epsilon_{B,3}$), the fraction of the shock internal energy that is partitioned to electrons in region 2 ($\epsilon_e$), and the electron energy spectral index in regions 2 ($\gamma_{2}$) and 3 ($\gamma_{3}$). The $\epsilon_{e,3}$ is not regarded as a free parameter because of the implicit condition $\epsilon_{e,3} + \epsilon_{B,3} = 1$ in region 3 (Dai 2004; Yu & Dai 2007; Geng et al. 2016, 2018).

Uniform priors on $\theta_v$, $\theta_{j}$, $\log B_p$, $\log E_{K,\text{iso}}$, $\log n_1$, $\log \epsilon_{B,2}$, $\log \epsilon_{B,3}$, $\log \epsilon_e$, $p_2$, and $p_3$ are adopted in this paper. In order to explore a parameter space as large as possible, we set a wide enough range for the priors, except for $\theta_{j}$. Abbott et al. (2017a) derived $\theta_{j} \leq 56^\circ$ at 90% credible intervals with a low-spin prior by using the distance measured independently by GW. Finstad et al. (2018) obtained $\theta_{j}$ with the distance measurement from Cantoni et al. (2018) and the GW data from Abbott et al. (2017a). They

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*The data were updated on 2021 May 3 and can be obtained at [http://www.tauceti.caltech.edu/kunal/gw170817/](http://www.tauceti.caltech.edu/kunal/gw170817/)."
The uncertainties of the best-fitting parameters are measured as 1σ confidence ranges.

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Table 1
| Parameter | Prior A | Result A | Prior B | Result B |
|-----------|---------|----------|---------|----------|
| $\theta_0$ (rad) | [0, 1] | $0.12^{+0.00}_{-0.00}$ | [0, 1] | $0.06^{+0.01}_{-0.01}$ |
| $\theta_i$ (rad) | [0.23, 0.7] | $0.23^{+0.00}_{-0.00}$ | [0, 0.7] | $0.14^{+0.01}_{-0.01}$ |
| $\log[B_{\text{post}}]$ | [10, 14] | $13.21^{+0.02}_{-0.02}$ | [10, 14] | $13.22^{+0.03}_{-0.03}$ |
| $\log[E_{\text{iso}}]$ | [49, 54] | $52.00^{+0.06}_{-0.06}$ | [49, 54] | $52.69^{+0.85}_{-0.85}$ |
| $\log f_3$ | [1, 3] | $1.69^{+0.04}_{-0.04}$ | [1, 3] | $1.81^{+0.06}_{-0.06}$ |
| $\log r$ (cm$^{3}$) | $[-6, 0]$ | $-4.39^{+0.05}_{-0.05}$ | $[-6, 0]$ | $-4.44^{+0.07}_{-0.07}$ |
| $\log \beta_{\text{3}}$ | $[-7, -0.5]$ | $-3.98^{+0.03}_{-0.03}$ | $[-7, -0.5]$ | $-3.55^{+0.03}_{-0.03}$ |
| $\log \beta_{\text{3}}$ | $[-7, -0.5]$ | $-5.41^{+0.03}_{-0.03}$ | $[-7, -0.5]$ | $-4.44^{+0.04}_{-0.04}$ |
| $\log c_{\text{r}}$ | $[-7, -0.5]$ | $-1.02^{+0.02}_{-0.02}$ | $[-7, -0.5]$ | $-2.62^{+0.04}_{-0.04}$ |
| $p_2$ | [2, 3] | $2.02^{+0.01}_{-0.01}$ | [2, 3] | $2.03^{+0.02}_{-0.02}$ |
| $p_3$ | [2, 3] | $2.25^{+0.03}_{-0.03}$ | [2, 3] | $2.20^{+0.01}_{-0.01}$ |

$\chi^2$/dof \ldots | 205.25/66 | \ldots | 149.32/66

Note. The uncertainties of the best-fitting parameters are measured as 1σ confidence ranges.

In particular, our model can reproduce the slowly rising phase of the early-time lightcurves. Instead of invoking a structured jet, our model suggests that the initial slowly rising lightcurves are a consequence of the peak time difference between the FS emission and the RS emission. The FS emission reaches a peak when the Lorentz factor of the jet is $\Gamma \sim 1/\sqrt{(\theta_i - \theta_i)}$, while the peak time of the RS emission is roughly equal to the spin-down timescale of the NS (Geng et al. 2016). In our fitting, the peak times of the FS and RS emissions are about 50 days and 150 days, respectively, and the superposition of these two components flattens the radio–X-ray lightcurves during this period, although the emission of each component rises sharply. The late-time X-ray afterglow of GRB 170817A shows a clear excessive emission compared to the estimated emission from the off-axis structured jet model (Hajela et al. 2021b). This excess could be explained by invoking additional emission components, e.g., kilonova afterglow (Hajela et al. 2019; Troja et al. 2020; Hajela et al. 2021b), accretion-powered emission (Hajela et al. 2021b; Ishizaki et al. 2021), or energy injection from the NS (Troja et al. 2020; Hajela et al. 2021b). Our model can reproduce a shallower late-time decay in the X-ray lightcurve without invoking an additional energy source, but cannot reproduce a late-time rise, as shown in Figure 2. Moreover, our model can give a natural explanation of the late-time harder spectrum (Hajela et al. 2021b) due to the change of composition and a relatively small p from the FS. The transition of the blast wave dynamics from the relativistic phase to the subrelativistic phase can also lead to a shallower decay in the late-time lightcurves without spectral evolution.

Figure 3 shows the best-fitting results for apparent velocity. Consistency between the model and the data suggests that our model can also reproduce the superluminal apparent motion between 75 days and 230 days after the merger. We also plot the dimensionless apparent velocity $\beta_{\text{app}}$ and Lorentz factor $\Gamma_j$ of the location, which is along the edge of the jet and closest to the line of sight (LOS) in Figure 3. One can see $\beta_{\text{app}}$ reaches the maximum value $\beta_{\text{app,max}} = \sqrt{\beta_j^2 - 1} \approx 1$, when $\Gamma_j = 1/\sin(\theta_i - \theta_i) \approx 9.1$ (Zhang 2018). The dimensionless apparent velocity of the flux centroid $\beta_{\text{app}}$ traces $\beta_{\text{app}}$ at early times, but $\beta_{\text{app}}$ is clearly larger than $\beta_{\text{app}}$ at late times. As shown in Figure 3, we also plot the apparent velocity of the FS flux centroid $\beta_{\text{app,FS}}$ and the RS flux centroid $\beta_{\text{app,RS}}$. There is almost no difference between $\beta_{\text{app,FS}}$ and $\beta_{\text{app,RS}}$, which means that $\beta_{\text{app}}$ is larger than $\beta_{\text{app}}$, which is not because of the RS emission from the $e^+e^-$ pair wind. In order to illustrate this discrepancy, we show the predicted source radio images at 75 days, 207.4 days, and 230 days seen by the observer in Figure 4. The black plus sign marks the location that is closest to the LOS, and the white plus sign marks the flux centroid. One can see the proper motion of the flux centroid is caused by three variations: the movement of the jet relative to the observer, the variation of the radio afterglow image size, and the changes in the location of the flux centroid relative to the jet. All these variations would keep the flux centroid away from the observer for an off-axis configuration. Therefore, a relatively large apparent velocity of the flux centroid is expected in late times.

Hajela et al. (2019) reported GRB 170817A radio observations using VLBI with an effective angular resolution of 1.5 × 3.5 mas. They found that the source radio image appears compact and apparently unresolved, and estimated that the apparent size of the radio source is constrained to be smaller than 2.5 mas (90% confidence level) at 207.4 days after the burst. In order to decide the size of our predicted source radio
images, we adopt an elliptical Gaussian function to fit the images. The MCMC method is adopted to reach the best fit to the images. We derive that the size of our predicted images from Results A and B at 207.4 days are about 2.4 \times 0.4 \text{mas} and 3.8 \times 1.5 \text{mas}, respectively. This is consistent with the expectation that a larger viewing angle leads to a smaller size image due to the projection effect. The predicted size from Result A is consistent with the observational constraint, whereas the size from Result B is slightly larger. Although we cannot rule out Result B due to the size of the real observed image of our model, Result A is more promising than Result B.

Table 1 shows the best-fitting parameters and their 1σ uncertainties by our fitting. The best-fitting parameters give \( \theta_\parallel \approx 7.0 \), which is consistent with the typical jet opening angle (e.g., Frail et al. 2001; Wang et al. 2015, 2018). The derived \( \theta_\parallel \approx 13^\circ \) reaches the lower limit on the viewing angle by combining GW and EM constraints (e.g., Finkad et al. 2018; Abbott et al. 2019). An NS with \( B_p \approx 1.6 \times 10^{13} \text{G} \) is needed in our fitting. Here \( B_p \) is mainly determined by \( \tau_{\text{sd}} \), while \( \tau_{\text{sd}} \) is roughly equal to the peak time of the flux from the RS (Geng et al. 2016), and also roughly equal to the peak time of the afterglow (\( \sim 150 \text{ days} \)) in our fitting. Therefore, \( B_p \approx 10^{13} \text{G} \) can be determined according to \( \tau_{\text{sd}} \approx 150 \text{ days} \). The isotropic kinetic energy \( E_{K,\text{iso}} \approx 1 \times 10^{52} \text{erg} \) corresponds to the true kinetic energy of the jet \( E_K = E_{K,\text{iso}}(1 - \cos \theta_j) / 2 \approx 4 \times 10^{49} \text{erg} \), which is comparable to the kinetic energy in the jet core inferred from structured jet models (e.g., Hajela et al. 2019; Lamb et al. 2019; Troja et al. 2019; Ryan et al. 2020). The initial Lorentz factor \( \Gamma_0 \approx 49 \) is lower than that obtained by the structured jet models. In addition, the microphysics parameters we derived are \( \epsilon_{R,2} \approx 1 \times 10^{-5}, \epsilon_{B,3} \approx 4 \times 10^{-6}, \epsilon_{e,2} \approx 0.1, \epsilon_{e,3} \approx 1, p_2 \approx 2.0, \) and \( p_3 \approx 2.3 \). Figure 5 displays the corner plots showing the results of our MCMC parameter estimation. There is a strong degeneracy between \( E_{K,\text{iso}} \) and \( n_1 \), \( E_{K,\text{iso}} \) and \( \epsilon_{R,2} \), and \( n_1 \) and \( \epsilon_{R,2} \), which leads to poor limitations on these parameters.

4. Discussion and Conclusions

Supposing the GRB 170817A prompt emission originates from internal dissipation of the jet energy, the observed off-axis values of physical quantities of the prompt emission can be corrected to on-axis values via the angle-dependent Doppler factor (however, a cocoon shock breakout as the origin of the prompt emission has been suggested, e.g., Kashiwal et al. 2017; Bromberg et al. 2018; Gottlieb et al. 2018). For the GRB duration \( T_{90} \) and the peak of the GRB energy spectrum \( E_p \), one has

\[
\frac{T_{90,\text{off}}}{T_{90,\text{on}}} = \frac{E_{p,\text{on}}}{E_{p,\text{off}}} = \frac{D(0)}{D(\theta_\parallel - \theta_\parallel)} = \frac{1 - \beta \cos(\theta_\parallel - \theta_\parallel)}{1 - \beta},
\]

while for the isotropic \( \gamma \)-ray energy of prompt emission \( E_{\gamma,\text{iso}} \), one has

\[
\frac{E_{\gamma,\text{iso,off}}}{E_{\gamma,\text{iso,off}}} \approx \left[ \frac{D(0)}{D(\theta_\parallel - \theta_\parallel)} \right]^2 \left[ 1 - \beta \cos(\theta_\parallel - \theta_\parallel) \right]^2.
\]

Using the observed quantities for GRB 170817A, \( T_{90,\text{off}} \approx 2 \text{ s}, E_{p,\text{off}} \approx 200 \text{ keV}, E_{\gamma,\text{iso,off}} \approx 5.3 \times 10^{46} \text{erg} \) (Abbott et al. 2017c), and our derived parameters, \( \theta_\parallel \approx 0.12, \theta_\parallel \approx 0.23, \) and \( \Gamma_0 \approx 49 \), one can derive the on-axis values, \( T_{90,\text{on}} \approx 0.06 \text{ s}, E_{p,\text{on}} \approx 6.2 \text{ MeV}, \) and \( E_{\gamma,\text{iso,off}} \approx 5.4 \times 10^{40} \text{erg} \). The derived \( T_{90,\text{on}} \) falls into the \( T_{90} \) distribution of sGRBs (e.g., Kouveliotou et al. 1993). The derived \( E_{p,\text{on}} \) is larger than the typical value (several hundred keV) but is still consistent with the wide \( E_p \) distribution of sGRBs (e.g., Gruber et al. 2014). After the correction, the energy released during the prompt emission phase of GRB 170817A is comparable to the sGRBs at low redshifts. For example, the short GRB 150101B jointly detected by Fermi/GBM and Swift/BAT has a redshift \( z = 0.1343 \pm 0.0030 \), which is the second nearby sGRB. At this redshift, the isotropic energy released in the \( \sim 10-1000 \text{ keV} \) energy band is \( E_{\gamma,\text{iso}} \approx 1.3 \times 10^{49} \text{erg} \) (Fong et al. 2016). GRB 160821B, the lowest redshift sGRB identified by Swift, has a redshift \( z = 0.162 \) (Levan et al. 2016), and its isotropic energy is \( E_{\gamma,\text{iso}} \approx 2.1 \times 10^{50} \text{erg} \) in the \( 8-1000 \text{ keV} \) range (Lii et al. 2017). Consistency between the on-axis values for GRB 170817A and typical values observed for sGRBs suggests that our model can reproduce the prompt emission of GRB 170817A.

The derived NS surface magnetic field strength is \( B_p \approx 10^{13} \text{G} \) in our fitting, which is more than one order of magnitude higher than previous results. For example, Ai et al. (2018) constrained \( B_p \) to be lower than \( \sim 10^{12} \text{G} \) if a long-lived NS survives after the merger. The kilonova observations are the main constraints on \( B_p \). One can directly derive the constraint on \( B_p \) based on the Arnett Law: peak luminosity of the kilonova equals the heating rate at the peak time, i.e., \( L_{\text{peak}} \approx \dot{Q}(t_{\text{peak}}) \) (Arnett 1982). The kilonova associated with GW170817 has a peak luminosity \( L_{\text{peak}} \approx 10^{44} \text{erg} \) at 0.5 days.

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\( \text{This constraint requires the ellipticity of the NS to be smaller than} \sim 10^{-4}, \) which is consistent with the implicit condition of our model. By default, the rotational energy loss is dominated by magnetic dipole radiation rather than GW radiation in our model, i.e., the luminosity of GW emission should be less than the luminosity of magnetic dipole emission, which allows us to derive the upper limit of ellipticity \( \epsilon < 5 \times 10^{-3} \) for \( B_p \approx 1.5 \times 10^{13} \text{G} \).

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\( \text{Figure 4. The relative position of 4.5 GHz radio images at 75 days (upper), 207.4 days (middle), and 230 days (lower) as seen by the observer. The white plus sign is the location of the flux centroid. The black plus sign is the location closest to the LOS. Purple ellipses are the best-fitting elliptical Gaussian showing the sizes (FWHM) of the images.} \)
after the merger. For a long-lived NS as a post-merger remnant, the heating of the kilonova ejecta usually comes from two components: radioactive $r$-process heating, and magnetic dipole spin-down heating, i.e., $Q = Q_{\text{ra}} + Q_{\text{md}}$. Therefore, one can write $Q_{\text{md}}(t_{\text{peak}}) = \eta L_{\text{sd}}(t_{\text{peak}}) \lesssim L_{\text{peak}}$, where $L_{\text{sd}}$ is the spin-down luminosity, and $\eta$ is a fraction of $L_{\text{sd}}$ that is used to heat the ejecta. Since $\tau_{\text{sd}} \gg t_{\text{peak}}$, one has $L_{\text{sd},0} = 9.64 \times 10^{44} B_{13}^{\gamma} \lesssim \eta^{-1} L_{\text{peak}}$. If one adopts $0.1 < \eta < 1$ as suggested by Yu et al. (2013), then $B_{\gamma} \lesssim 10^{11} - 10^{12}$ G, which is generally consistent with the result from Ai et al. (2018). However, so far there are no simulations providing the exact value of $\eta$, and $\eta$ could be much smaller than unity for the following reasons: (1) if a fraction of spin-down energy is reflected by the ejecta walls and the large pair optical depth through the nebula behind the ejecta, a low efficiency of the spin-down luminosity used to thermalization is expected, as suggested by Metzger & Piro (2014); (2) a fraction of the spin-down energy could be converted to the kinetic energy of the kilonova ejecta rather than heat the ejecta (e.g., Wang et al. 2016); and (3) the spin-down powered outflow could be collimated along the GRB jet direction due to the interaction between the outflow and the ejecta (e.g., Bucciantini et al. 2012). According to the derived

Figure 5. A corner plot showing the results of our MCMC parameter estimation for the relativistic $e^+e^-$ pair wind model. Our best-fitting parameters and corresponding $1\sigma$ uncertainties are shown with the black dashed lines in the histograms on the diagonal.
$B_p$ and the peak luminosity of kilonova associated with GW170817, $\eta$ can be as low as $\sim 10^{-3}$ in our estimation.

In this paper, we fit the multiwavelength afterglow lightcurves and the VLBI proper motion of GRB 170817A based on the relativistic $e^+e^-$ pair wind model. The MCMC method is adopted to obtain the best-fitting parameters. We find that the overall quality of the fitting is good, indicating that our relativistic $e^+e^-$ pair wind model can explain the GRB 170817A afterglow. We obtain a set of best-fitting parameters using the prior of the viewing angle ranging from 0.23 rad to 0.7 rad provided by the GW and EM observations. The best-fitting value $\theta_v \approx 0.23$ is close to the lower limit of this prior, indicating that our model prefers a smaller viewing angle. If the prior of $0 \leq \theta_v \leq 0.7$ is allowed, the best-fitting value of the viewing angle can be as low as $\sim 0.14$ rad. Additionally, our model can reproduce the prompt emission of GRB 170817A. An NS with $B_p \approx 1.6 \times 10^{13}$ G is needed in our fitting. Combining the derived $B_p$ and the kilonova observations, we find that the fraction of the spin-down luminosity that is thermalized and available to power the kilonova can be as low as $\sim 10^{-3}$. Our model can reproduce a late-time shallow decay in the X-ray lightcurve and predicts that the X-ray and radio flux will continue to decline in the next few years. In contrast, Hajela et al. (2021b) predicts that the X-ray and radio flux will keep increasing for at least a few years within the framework of the kilonova afterglow model, and the X-ray flux will remain constant or decay with index $-5/3$ in the fall-back accretion model (Ishizaki et al. 2021). Further observations of GRB 170817A afterglow may help verify or disprove our model.

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Software: emcee (Foreman-Mackey et al. 2013).

Appendix A

Dynamics and Radiation

There are four distinct regions when an ultrarelativistic $e^+e^-$ pair wind interacts with the jet and the medium: (1) the unshocked medium, (2) the shocked jet and medium, (3) the shocked wind, and (4) the unshocked wind. In the following, the quantities of region $i$ are denoted by subscript $i$. The comoving- and observer-frame quantities are marked with and without a superscript prime $'$, respectively. Neglecting the internal structure of the blast wave (Blandford & McKee 1976), and assuming that regions 2 and 3 move with the same Lorentz factor, i.e., $\Gamma_2 = \Gamma_3 = \Gamma$, the dynamics of such an FS-RS system can be solved by the energy conservation.

Let us first define a spherical coordinate system $(r, \theta, \phi)$, where $r$ is the distance from the coordinate origin, and $\theta$ and $\phi$ are the latitudinal and azimuthal angles, respectively. The GRB central engine is located at the coordinate origin, and the GRB jet axis is along the direction of $\theta = 0$. The observer lies on the $\phi = \pi/2$ plane, and $\theta_o$ is the angle between the LOS and the GRB jet axis. We divide the $\theta \in [0, \pi]$ and $\phi \in [0, 2\pi]$ into $M$ and $N$ parts, so that the GRB jet can be discretized into $M \times N$ grids, and each grid has a solid angle $d\Omega = \sin \theta d\theta d\phi$. For a top-hat jet model, which is adopted in this paper, the dynamical evolution for each grid is identical.

For any grid, the dynamical evolution per unit solid angle can be described as follows. Considering radiative loss, the total kinetic energy of region 2 is

$$E_2 = (\Gamma - 1)(M_{e3} + m_2)c^2 + (1 - \epsilon_2)(\Gamma - 1)m_2c^2.$$  \hfill (A1)

where $M_{e3}$ and $m_2$ are the rest masses of the initial GRB ejecta and the FS swept-up medium per unit solid angle. $\epsilon_2 = \epsilon_{2syn}/(\epsilon_{2syn} + \epsilon_{2ex})$ is the radiation efficiency of region 2, where $\epsilon_i$ is the fraction of the shock internal energy that is partitioned to electrons, and $\epsilon_{2syn}$ and $\epsilon_{2ex}$ are the synchrotron-cooling timescale and the comoving-frame expansion timescale, respectively (Dai & Lu 1999). Energy conservation requires that the change of the total kinetic energy of region 2 should be equal to the work done by region 3 to region 2 minus a fraction of thermal energy that is radiated from region 2:

$$dE_2 = R^2p_i'dR - \epsilon_2\Gamma(\Gamma - 1)dm_2c^2,$$  \hfill (A2)

where the comoving pressure of region 3 should be calculated by

$$p_i' = (1 - \epsilon_3)(\Gamma_{34} - 1)(\gamma_3\Gamma_{34} + 1)n_4'm_ec^2.$$  \hfill (A3)

Here $\gamma_3$ and $\epsilon_3$ are the adiabatic index and the radiation efficiency of region 3, $\Gamma_{34} = \Gamma_3\Gamma_4 - \Gamma_4\Gamma_3$ stands for the relative Lorentz factor between region 3 and 4, and $n_4' = n_4''$ is the comoving $e^+e^-$ number density of region 4. Combining Equations (A1)–(A3), the differential equation $d\Gamma/dR$ can be written in the form

$$d\Gamma = \frac{R^2[(1 - \epsilon_3)(\Gamma_{34} - 1)(\gamma_3\Gamma_{34} + 1)n_4'm_e - (-\Gamma^2 - 1)n_4m_p]}{M_4 + \epsilon_2m_2 + (1 - \epsilon_2)\Gamma_2m_2}.$$  \hfill (A4)

To solve the differential equation $d\Gamma/dR$, one needs to know the evolution of $m_3$ with distance $R$, which can be written as

$$\frac{dm_3}{dR} = R^2n_3'm_p.$$  \hfill (A5)

Furthermore, the rest mass of region 3 is obtained by Dai & Lu (2002)

$$\frac{dn_3}{dR} = n_3'(\gamma_{34}^{1/4}\Gamma_{34}/\Gamma_{33})n_4'm_e.$$  \hfill (A6)

Here $m_3$ is the rest mass of the RS swept-up medium per unit solid angle, $\beta_3$ is the dimensionless speed of region 3, and $\beta_3 \approx (\Gamma_3^2 - \Gamma_4^2)/(\Gamma_3^2 + \Gamma_4^2)$ is the relative dimensionless speed between regions 3 and 4.

In order to calculate the synchrotron and IC emission, we assume that a fraction of the shock internal energy is partitioned to magnetic fields $\xi_{B,i}$ and electrons $\epsilon_{e,i}$, and assume that electrons in regions 2 and 3 can be accelerated by the FS and the RS with a power-law distribution in energy $dN_e/d\gamma_e \propto \gamma_e^{-\gamma_{e,i}^{-1}}\gamma_{e,i}^{-\gamma_{e,i}^{-1}}$. Here $p_i$ is the electron energy spectral index in region $i$, $\gamma_{e,i}^{-1} = (m_p/m_e)n_{ei}^{-1} + (m_p/m_e)\epsilon_{e,i}$, and $\gamma_{e,ix}^{-1} = \Gamma_{ix}(\Gamma_{ix} - 1)/(\Gamma_{ix}^2 - 1)$ are the comoving-frame minimum electron Lorentz factors in regions 2 and 3, and $\gamma_{e,ix}^{-1} \approx \sqrt{6}\sigma_{q,i}/[\sqrt{\sigma_i B_i(1 + \gamma_i)}] \approx 10^3\sqrt{B_i(1 + \gamma_i)}$ is the maximum Lorentz factors in region $i$. The comoving magnetic
The final electron energy has a broken power-law distribution, since the electrons are cooled by synchrotron and IC radiation. By comparing the electron minimum Lorentz factor $\gamma_m$ and the electron cooling Lorentz factor $\gamma_c$, that can be written as

$$\gamma'_{c,i} = \frac{6\pi m_e c(1 + z)}{\sigma_T B_i^2 Y_{\text{obs}} (1 + Y)}.$$  

(A7)

two different regimes can be derived. If $\gamma'_{c,i} < \gamma'_{m,i}$, where all the electrons have cooled (the fast cooling regime), one has

$$\frac{dN'_e}{d\gamma'_{e_i}} \sim \begin{cases} \gamma'_e^{\gamma'_{m,i} - 2} & \gamma'_e \leq \gamma'_{c,i} \\ \gamma'_e^{\gamma'_{m,i} - (p + 1)} & \gamma'_e > \gamma'_{c,i} \end{cases}.$$  

(A8)

If $\gamma'_{m,i} < \gamma'_{c,i}$, where only a fraction of the electrons have cooled (the slow cooling regime), one has

$$\frac{dN'_e}{d\gamma'_{e_i}} \sim \begin{cases} \gamma'_e^{\gamma'_{m,i} - 2} & \gamma'_e \leq \gamma'_{c,i} \\ \gamma'_e^{\gamma'_{m,i} - (p + 1)} & \gamma'_e > \gamma'_{c,i} \end{cases}.$$  

(A9)

Once the electron distribution is determined, the synchrotron radiation power per unit solid angle of each grid in the region $i$ at the frequency $\nu'$ can be calculated as (Rybicki & Lightman 1979)

$$P'_{\text{syn}}(\nu') = \frac{3\alpha q_c B_i^4}{m_e c^2} \int_{\min(\gamma'_{m,i},\gamma'_{c,i})}^{\gamma'_{m,i}} \frac{dN'_e}{d\gamma'_{e_i}} \int_{\gamma'_{e_i}}^{\nu'} F(\nu'/\nu'_c) d\gamma'_{e_i}.\tag{A10}$$

Here $\nu' = (1 + z)\nu_{\text{obs}}/D$ is the synchrotron frequency in the comoving frame, where $\nu_{\text{obs}}$ is the observed frequency, $z$ is the redshift, and $D \equiv 1/(1 - \beta \cos\alpha)$ is the Doppler factor with $\cos\alpha = \cos\theta \cos\theta_s + \sin\theta \sin\phi \sin\theta_s$ in our assumed geometrical setting (the angle between the velocity direction of each grid and the LOS). $q_c$ is the electron charge, $\nu'_c = 3\gamma'_c q_c B_i^4/(4\pi m_e c)$ is the critical frequency of synchrotron radiation, $F(\nu'/\nu'_c) = (\nu'/\nu'_c)^p K_{5/3}(\nu d\nu)$, and $K_{5/3}(x)$ is the modified Bessel function of order 5/3.

In addition to the synchrotron radiation, we also consider the IC radiation from shock-accelerated electrons. The IC radiation includes two parts: the synchrotron self-Compton (SSC) radiation, and combined IC (CIC) radiation, i.e., photons in region $i$ are scattered by electrons in regions $j$ ($i \neq j$). The IC radiation power (per unit solid angle of each grid at the frequency $\nu'$) of electrons in the region $i$ scattered photons from region $j$ can be calculated as ($i = j$ for SSC and $i \neq j$ for CIC; Blumenthal & Gould 1970; Yu & Dai 2007)

$$P'_{\text{IC}}(\nu') = 3\pi \int_{\min(\gamma'_{m,i},\gamma'_{c,i})}^{\gamma'_{m,i}} \frac{dN'_e}{d\gamma'_{e_i}} \int_{\gamma'_{e_i}}^{\nu'} F(\nu'/\nu'_c) g(x, y) d\gamma'_e,$$  

where $\gamma'_{\min,i} = \max(\lfloor\gamma'_{c,i}\rfloor, \nu'/m_e c^2)$, $\nu'_{i,j,\min} = \nu'_m c^2/(4\gamma'_{e_i} \nu'_m c^2 - \Delta \nu')$, and $g(x, y) = 2y \ln(1 + 2y) - 2y(1 - y) + x^2/(2(1 + y)) (1 - y)$, with $x = 4\gamma'_{e_i} \nu'_{i,j}/m_e c^2$ and $\nu' = \nu'/[x(\gamma'_e c^2 - \Delta \nu')]$.

Finally, we integrate Equations (A10) and (A11) over the equal arrival time surface (EATS) to get the total flux density at the observed frequency $\nu_{\text{obs}}$:

$$F_{\nu_{\text{obs}}} = \frac{1 + z}{4\pi D^2} \int_{\text{EATS}} D^3 \{ P'_{\text{syn}}(\nu') + P'_{\text{IC}}(\nu') \} d\Omega$$

(A13)

For a given observed time $t_{\text{obs}}$, the emission radius $R_\alpha$ at each grid (i.e., the EATS) is obtained by

$$t_{\text{obs}} = \{ 1 + z \} \int_0^{R_\alpha} \frac{1 - \beta \cos\alpha}{\beta c} dr \equiv \text{const.} \tag{A14}$$

**Appendix B**

**Proper Motion of the Flux Centroid**

In order to calculate the proper motion of the flux centroid, one needs to project the position of each grid at each moment onto the plane perpendicular to the LOS. We first convert the spherical coordinate system ($R, \theta, \phi$) to the Cartesian coordinate system ($x, y, z$) = ($R \sin \theta \cos \phi, R \sin \theta \sin \phi, R \cos \theta$). In the Cartesian coordinate system, the GRB jet axis is aligned with the $z$ direction, and the observer lies on the $y - z$ plane. We perform a coordinate rotation about the $x$-axis from ($x, y, z$) to ($x', y', z'$), after which LOS is aligned with the $z'$-axis, and the angle between the $z$-axis and the $z'$-axis is $\theta_s$, as shown in Figure 6. The coordinate transformation from ($x, y, z$) to ($x', y', z'$) is given by

$$x' = x,$$  

(B1)

$$y' = y \cos\theta_s - z \sin\theta_s,$$  

(B2)

$$z' = z \cos\theta_s + y \sin\theta_s.$$  

(B3)

For a given observer time $t_{\text{obs}}$, the projected position of each grid on the EATS is given by $r'_k = (x'_k, y'_k) = (R_s \sin \theta \cos \phi, R_s \sin \theta \sin \phi, R_s \cos \theta)$, since the flux centroid is defined as the mean location of a distribution of flux density in space, the location of the flux centroid on the plane perpendicular to the LOS can be expressed as

$$r'_k = (x'_k, y'_k) = \int_{\text{EATS}} \frac{f_{\nu_{\text{obs}}}^{(x'_k, y'_k)}}{f_{\nu_{\text{obs}}}^{(x'_k, y'_k)}} dS,$$  

where $dS$ is the area of each grid projected into the plane of the sky. Because the jet is symmetric about the $y - z$ plane, the flux centroid can also be described by ($0, y'_k$) = ($0, \int_{\text{EATS}} f_{\nu_{\text{obs}}}^{(x'_k, y'_k)} dS$). For the observer, the angular
position of each grid is \((0, y_D^c/D_A)\), where \(D_A = D_L/(1+z)^2\) is the angular diameter distance. Finally, the average apparent velocity of the flux centroid over a time interval \(t_{\text{obs},j} - t_{\text{obs},i}\) can be written as

\[
v_{\text{app}} = \frac{y_{\text{fc},j}^c - y_{\text{fc},i}^c}{t_{\text{obs},j} - t_{\text{obs},i}},
\]

and the dimensionless velocity \(\beta_{\text{app}} = v_{\text{app}}/c\).

**Appendix C**

**Fitting Results from Prior B**

We also show the fitting results from priors with \(\theta_v \in [0, 0.7]\) (Prior B) in Figures 7–10.

**Figure 6.** Two coordinate systems before (blue) and after (orange) transformation. The jet direction is along the \(z\)-axis, while the LOS is aligned with the \(z'\)-axis.

**Figure 7.** Relativistic \(e^+e^-\) pair wind model fit to the multiwavelength afterglow lightcurves of GRB 170817A. The dashed and dotted curves represent the emission from the FS and RS, respectively. The solid curves are the total emission lightcurves.
Figure 8. Relativistic $e^+e^-$ pair wind model fit to the VLBI proper motion of GRB 170817A afterglow. The mean dimensionless apparent velocity of the radio afterglow source $\beta_{app} = 4.1 \pm 0.5$ between 75 days and 230 days after the merger from Mooley et al. (2018c) yields the data point used to fit. The solid green, red, and blue curves show the evolution of dimensionless apparent velocity of the flux centroid based on our best-fitting parameters when considering FS emission, RS emission, and total emission, respectively. The blue dashed and dotted curves denote $\beta_{app,j}$ and $\Gamma_j$. The blue solid horizontal line represents the mean apparent velocity between 75 and 230 days derived from our model.

Figure 9. The relative position of 4.5 GHz radio images at 75 days (upper), 207.4 days (middle), and 230 days (lower) as seen by the observer. The white plus sign is the location of the flux centroid. The black plus sign is the location closest to the LOS. Purple ellipses are the best-fitting elliptical Gaussian showing the sizes (FWHM) of the images.
Figure 10. A corner plot showing the results of our MCMC parameter estimation for the relativistic $e^+e^-$ pair wind model. Our best-fitting parameters and corresponding 1σ uncertainties are shown with the black dashed lines in the histograms on the diagonal.

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