Broadband Emission from a Kilonova Ejecta-Pulsar Wind Nebula System: Late-Time X-ray Afterglow Rebrightening of GRB 170817A

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ABSTRACT
We study the broadband radiation behavior of a kilonova ejecta-pulsar wind nebula (PWN) system. In this model, we jointly fit the observations of AT 2017gfo in UV-optical-IR bands and the late-time X-ray afterglow of GRB 170817A. Our work shows that a PWN powered by the remnant neutron star (NS) post GW170817 event could affect the optical transient AT 2017gfo and re-brighten the late-time X-ray afterglow of GRB 170817A. The PWN radiation will regulate the trend of future X-ray observations from a flattening to a steep decline until some other sources (e.g., a kilonova afterglow) become dominant. The restricted ranges of the central NS parameters in this work are consistent with the previous works based on the observations of AT 2017gfo only. In addition, the new fitting result indicates that the NS wind is highly magnetized. We point out that the radio and X-ray emission from a kilonova ejecta-PWN system could be an important electromagnetic feature of binary NS mergers when a long-lived remnant NS is formed. Therefore, observations of a kilonova ejecta-PWN system will provide important information to inferring the nature of a merger remnant.

Key words: Gravitational waves – gamma-ray burst: individual (GRB 170817A) – stars: neutron – pulsars: general

1 INTRODUCTION

Compact binary mergers are the main sources of gravitational wave (GW) events in the frequency range of the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) and the Advanced Virgo GW detectors. Among them, the mergers of binary neutron star (NS) and NS-black hole (BH) draw a lot of attention since they are also potential sources of electromagnetic radiation (EM). The first GW signal from a NS–NS merger was detected by the advanced LIGO and Virgo detectors on 2017 August 17 12:41:04 UT (Abbott et al. 2017b).

The nature of the merger remnant of the GW170817 event has been debated so far. Based on the observational fact that the prompt EM signal is delayed about 1.7 seconds after the GW signal as well as the sufficiently heavy gravitational mass of the merger remnant (Abbott et al. 2017a; Goldstein et al. 2017; Savchenko et al. 2017; Zhang et al. 2018), a short-lived NS remnant seems likely (e.g., Metzger et al. 2018). Although the time-lag between the GW and EM signals points to a short-lived NS remnant, recent works on numerical simulation and analytical calculations have attributed this phenomenon to the effect of jet propagation (e.g., Beniamini et al. 2020; Hamidani et al. 2020; Hamidani & Ioka 2021; Lyutikov 2020; Lazzati & Perna 2019; Lazzati et al. 2020; Ren et al. 2020; Pavan et al. 2021, and reference therein). Therefore, the observations are not inconsistent with the view that a long-lived NS was formed after the merger. Yu et al. (2013) first suggested the possibility of the existence of a remnant-NS-powered kilonova, namely a mergernova. Works have been done under this picture to comprehend the behavior of AT 2017gfo (e.g., Matsumoto et al. 2018; Li et al. 2018; Yu et al. 2018; Ren et al. 2019).

The observations of the GRB 170817A afterglow have lasted about four years (e.g., Makhathini et al. 2020; Balasubramanian et al. 2021; Hajela et al. 2021a; Troja et al. 2021). The popular interpretation of the origin of GRB 170817A afterglow nowadays is an off-axis observed structured jet (e.g., Ren et al. 2020). Some other scenarios have been proposed, say, a refreshed jet (Lamb et al. 2020) or an \( e^{±}\)-wind-injected jet (Li & Dai 2021). About 3.4 years after the trigger of the GW170817 event, the Chandra X-ray Observatory detected an X-ray source located at the position of GRB 170817A/AT 2017gfo (Hajela et al. 2021a,b). But the unabsorbed X-ray flux derived from the observed data exceeds the conjectural extension based on the off-axis structured jet model. Since the flux excess is obvious at the X-ray band but undetected at the radio band, an additional source instead of the GRB jet external shock to explain the data is naturally needed. At present, the kilonova afterglow gets increasing attention. It has been supposed to be the cause of GRB 170817A re-
brightening (Hajela et al. 2021a; Nedora et al. 2021). However, some other explanations, e.g., the \( e^\pm \)-wind-injected jet (Geng et al. 2018; Li & Dai 2021), the fall-back accretion of central BH (Ishizaki et al. 2021a,b; Metzger & Fernandez 2021), and maybe the counter-jet (Li et al. 2019; Troja et al. 2021) are possible scenarios.

In this paper, we introduce a different scenario in which a pulsar wind nebula (PWN) is powered by the remnant NS of the GW170817 event to explain the optical transient AT 2017gfo and the late time rebrightening X-ray afterglow of GRB 170817A. This paper is organized as follows. In Section 2 we present our numerical model. In Section 3 we describe the fitting process in detail. We discuss the significance of the fitting results in Section 4. We summarize our conclusions in Section 5. Throughout this work, we use the notation \( Q = 10^5 Q_x \) in the c.g.s. unit unless noted otherwise, and \( D_L = 40 \) Mpc is the luminosity distance of AT 2017gfo/GRB 170817A.

2 THE MODEL

Similar to the Crab supernova remnant, a PWN could be formed if a pulsar is left at the center of a merger remnant. In the previous works of an energy-injected kilonova, the released magnetic dipole (MD) radiation from the central NS is considered as an injected thermalization energy source (e.g., Yu et al. 2013, 2018; Kasen et al. 2015). A PWN is formed by the interaction between the pulsar wind and ejecta after the merger (e.g., Koter 2013; Murase et al. 2018). Based on those works, Ren et al. (2019) considered a PWN embedded in the merger ejecta to explain the behavior of AT 2017gfo. Wu et al. (2021) adopted the same picture in their study of GRB 160821B afterglow with slightly different modeling.

The spin-down energy of the central NS first powers a PWN. Then, nonthermal photons radiated from the PWN will cross the ejecta shell and some photons are absorbed to thermalize the ejecta material while the other photons escaping from the PWN could impact the observations. The observed flux thus consists of the emission \( F^b_\nu \) from the ejecta and the leaked part \( F^\text{leak}_\nu \) from the PWN, i.e.,

\[
F^\text{tot}_\nu = F^b_\nu + F^\text{leak}_\nu.
\]

The estimates of \( F^b_\nu \) and \( F^\text{leak}_\nu \) are given in Sections 2.1 and 2.2, respectively.

After the ejecta becomes transparent to X-ray photons, an additional observable signal from the PWN may appear. Both the early kilonova behavior and the late X-ray band observations may be affected. The kilonova ejecta-PWN system was proposed in the previous work (Ren et al. 2019). We present some key formulas and new refinements below.

2.1 Emission from the ejecta

The dynamics and emission of the quasi-isotropic ejecta are implemented based on a simplified radiation transfer model given by Kasen & Bildsten (2010) and Metzger (2019). The merger ejecta expanding homologously is divided into \( N(\gg 1) \) layers with different expansion velocities \( v_i \), where \( v_1 = v_{\text{min}} \) and \( v_N = v_{\text{max}} \). The location of the \( i \)th layer at time \( t \) is \( R_i = v_i t \), and the mass of the \( i \)th layer is \( m_i = \int_{R_{i-1}}^{R_i} 4\pi r^2 \rho_\epsilon(r,t) \, dr \) with (Nagakura et al. 2014)

\[
\rho_\epsilon(r,t) = \frac{(\delta - 3) M_{ej}}{4\pi R_{\text{max}}^3} \left( \frac{R_{\text{min}}}{R_{\text{max}}} \right)^{3-\delta} - 1 \left( \frac{r}{R_{\text{max}}} \right)^{-\delta},
\]

where \( M_{ej} \) is the total mass of the ejecta. Evolution of the initial energy \( E_i \) for the \( i \)th layer can be described by

\[
\frac{dE_i}{dt} = (1 - e^{-\Delta t_i}) e^{-\tau_i} \xi L_{\text{md}} + m_b \eta_{\text{th}} = \frac{E_i dR_i}{R_i dt} - L_i.
\]

Here, in each layer, the first term on the right-hand side describes the absorption of PWN emission, the second term is the radioactive heating rate, the third term is the adiabatic cooling rate, and the last term is the radiation cooling rate, respectively. The details about the parameters are presented as follows.

(i) The power of the pulsar wind \( L_{\text{md}} \) from the NS can be estimated by MD radiation, i.e.,

\[
L_{\text{md}}(t) = L_{\text{md},0} \left( 1 + \frac{t}{t_{\text{ad}}} \right)^{-\alpha}
\]

with

\[
L_{\text{md},0} = \frac{B_p^2 R_p^4 \Omega_p^4}{6c^3} = 9.6 \times 10^{42} R_6^2 B_{p,12}^2 P_{-3}^{-4} \text{ erg \cdot s}^{-1},
\]

where \( \Omega_p \), \( R_p \), \( B_p \) and \( c \) are the initial angular frequency, the radius, the surface polar magnetic field, the initial spin period of the NS, and the speed of light, respectively. Based on the fitting results of Yu et al. (2018) and Ren et al. (2019), the spin-down timescale \( t_{\text{ad}} \) can be taken to be

\[
t_{\text{ad}} = \frac{5c^5}{128G \xi c^2 \Omega_p^5} = 9.1 \times 10^5 \text{c}^{-4} \text{I}_{45}^{-1} P_{-3}^4 \text{ s},
\]

with \( \alpha = 1 \) for the GW-dominated spin-down loss regime, where \( G \) is the gravitational constant, \( \xi \) is the stellar moment of inertia, and \( c \) is the NS ellipticity. \( \xi \) describes the fraction of \( L_{\text{md}} \) that can be absorbed by the ejecta. In addition, \( \tau_i \) is the optical depth from the innermost layer to the \( i \)th layer and can be described by \( \tau_i = \sum_{i-1}^{\text{th layer}} \Delta \tau_i \) with \( \Delta \tau_i = \int_{R_i}^{R_{i+1}} \kappa \rho(r) \, dr \).

(ii) The radioactive power per unit mass \( \dot{q}_i \) and the thermalization efficiency of the radioactive power \( \eta_{\text{th}} \) can be estimated by (Korobkin et al. 2012; Barnes et al. 2016; Metzger 2019)

\[
\dot{q}_i = 4 \times 10^{18} \left[ \frac{1}{2} - \frac{1}{\pi} \arctan \left( \frac{t - t_0}{\sigma} \right) \right]^{1.3} \text{ erg \cdot s}^{-1} \cdot \text{g}^{-1}
\]

and

\[
\eta_{\text{th}} = 0.36 \left[ \exp \left( -0.56 t_{\text{day}} \right) + \frac{\ln(1 + 0.34 t_{\text{day}})}{0.34 t_{\text{day}}} \right],
\]

respectively. Here, \( t_0 = 1.3 \) s, \( \sigma = 0.11 \) s, and \( t_{\text{day}} = t/1 \) day.

(iii) The luminosity of the \( i \)th layer \( L_i \) is estimated by

\[
L_i = \frac{E_i}{\max \{ t_i^\text{d}, t_i^\text{k} \}}
\]

where the diffusion timescale \( t_i^\text{d} \) of photons reads

\[
t_i^\text{d} \cong \frac{\kappa}{\beta R_i c} \sum_{j=i}^{N-1} m_j,
\]
where \( t'_b = R_b/c \) is the light crossing time. Here \( \beta \simeq 13.7 \) is adopted (Arnett 1982).

The total bolometric luminosity \( L_{\text{bol}} \) of the ejecta is estimated by

\[
L_{\text{bol}} = \sum_{i=1}^{N-1} L_i. \tag{11}
\]

We assume that a blackbody spectrum of the ejecta is emitted from the photosphere at \( R_{\text{ph}} \) and the effective temperature \( T_{\text{eff}} \) is described as (Yu et al. 2013; Xiao et al. 2017; Li et al. 2018)

\[
T_{\text{eff}} = \left( \frac{L_{\text{bol}}}{4\pi\sigma_{\text{SB}}R_{\text{ph}}^2} \right)^{1/4}, \tag{12}
\]

where \( \sigma_{\text{SB}} \) is the Stephan-Boltzmann constant. The photosphere radius \( R_{\text{ph}} \) is estimated by setting \( \tau_{\text{ph}} = \int R_{\text{ph}}^\infty \rho(r)dr = 1 \) since \( \tau_{\text{tot}} > 1 \). If \( \tau_{\text{tot}} \leq 1 \), we fix \( R_{\text{ph}} \) to \( R_{\text{min}} \). The flux density at frequency \( \nu \) from the ejecta is given by

\[
F_{\nu} = \frac{2\pi h\nu^3}{c^2} \exp(h\nu/kT_{\text{eff}}) - 1 \frac{R_{\text{ph}}^2}{D_L^2}. \tag{13}
\]

where \( h \) is the Planck constant and \( k \) is the Boltzmann constant.

### 2.2 Emission from the PWN

At the interface between the shocked and unshocked pulsar wind (“termination shock”), electrons and positrons (leptons, hereafter) carried in the cold pulsar wind are accelerated, and the magnetic field is amplified. The accelerated leptons and the amplified magnetic field fill the PWN out to the radius \( R_{\text{PWN}} \). Assuming \( \epsilon_B \) to describe the fraction of the magnetic energy density of the total energy density behind the shock, the magnetic energy density \( U_B^{\text{PWN}} \) in the PWN can be parameterized as (Tanaka & Takahara 2010, 2013; Murase et al. 2016)

\[
U_B^{\text{PWN}} = \frac{B_{\text{PWN}}^2}{8\pi} = \frac{3}{4\pi} \epsilon_B R_{\text{PWN}}^{-3} \int_{0}^{t} L_{\text{mod}}(s)ds. \tag{14}
\]

Here \( R_{\text{PWN}} \sim R_{\text{min}} \) is taken because the deceleration timescale of the ejecta is much larger than the scope of our calculation. A broken power-law is adopted to describe the energy distribution of leptons in the PWN (Murase et al. 2015),

\[
\frac{d\dot{n}_{\text{e}}}{d\gamma_{\text{e}}} \propto \begin{cases} \gamma_{\text{e}}^{-q_1}, & \gamma_M \leq \gamma_{\text{e}} < \gamma_b, \\ \gamma_{\text{e}}^{-q_2}, & \gamma_b \leq \gamma_{\text{e}} \leq \gamma_M, \end{cases} \tag{15}
\]

where \( q_1 \sim 1 - 2 (q_2 \sim 2 - 3) \) is the low (high)-energy spectral index, \( \gamma_M \sim 10^4 \sim 10^5 \) is the characteristic Lorentz factor of the accelerated leptons in the PWN, and \( \gamma_M (\gamma_M) \) is the minimum (maximum) Lorentz factor of leptons. In this work, we assume \( \gamma_M = 3 \) and \( \gamma_M = \sqrt{3m_e^2c^2/(8B_{\text{PWN}}^2q_e^2)} \) (Kumar et al. 2012), where \( q_e \) is the charge of leptons, and \( m_e \) is the electron mass.

For the synchrotron emission of the PWN, two break frequencies are related with the leptons’ property, i.e., the characteristic synchrotron frequency \( \nu_b \) corresponding to \( \gamma_b \), and the synchrotron cooling frequency \( \nu_c \) to \( \gamma_c = 6\pi m_e c/(\sigma_T B_{\text{PWN}}^2) \). The frequencies are expressed by

\[
\nu_i = \frac{3\gamma_i^{-3/2}B_{\text{PWN}}^2}{m_e c}, \quad i = b, c, m, M, \tag{16}
\]

where \( \sigma_T \) is the Thomson cross section (Sari et al. 1999). The synchrotron emission is described as follows correspondingly. In the fast-cooling regime \( (\nu_c < \nu_b) \), the synchrotron emission flux density \( \nu L_{\nu} \) at frequency \( \nu \) can be expressed by (Murase et al. 2016)

\[
\nu L_{\nu}^{\text{PWN}} \approx \frac{\xi L_{\text{mod}}}{2R_b} \left( \frac{\nu}{\nu_b} \right)^{3-2q_1} \left( \frac{\nu}{\nu_c} \right)^{3-2q_2}, \quad \nu_b \leq \nu \leq \nu_c, \tag{17}
\]

In the slow-cooling regime \( (\nu_c > \nu_b) \),

\[
\nu L_{\nu}^{\text{PWN}} \approx \frac{\xi L_{\text{mod}}}{2R_b} \left( \frac{\nu}{\nu_b} \right)^{3-2q_1} \left( \frac{\nu}{\nu_c} \right)^{3-2q_2}, \quad \nu_b \leq \nu \leq \nu_c, \tag{18}
\]

Where \( R_b \simeq (2 - q_1)^{-1} - (q_2 - 2)^{-1} \), the radiation efficiency \( \xi = \eta e \) with \( \eta = \min(1, (\nu_b/\nu_c)^{(q_2-2)/2}) \) (Fan & Piran 2006), and \( \epsilon_e = 1 - \epsilon_B \) is adopted. The critical synchrotron self-absorption (SSA) frequency \( \nu_c \) can be calculated with \( \tau_{\nu_c} = 1 \), and the SSA optical depth is estimated by (e.g. Panaitescu & Kumar 2004; Murase et al. 2014)

\[
\tau_{\nu_c} \simeq \xi q_1 n_{\text{ext}} R_{\text{PWN}}^2 B_{\text{PWN}}^2 \gamma_{\text{e}}^{-1} \left( \frac{\nu}{\nu_b} \right)^{-q_1/2}, \tag{19}
\]

where \( \xi q_1 \approx 5/3 \), and \( n_{\text{ext}} \approx n_{\text{PWN}} + n_{\text{e}} \) is the number density of leptons. Here, \( n_{\text{PWN}} \approx L_{\text{mod}}/(4\pi R_{\text{PWN}}^2\gamma_{\text{e}} m_e c^2) \) and \( n_{\text{e}} \approx 3M_{\odot}/(4\pi n_{\text{PWN}} R_{\text{PWN}}^3) \). Based on Equations (17) and (18), one can have \( \int_0^{R_{\text{max}}} L_{\nu} d\nu \approx \xi \eta e L_{\text{mod}} \). In this work, the effects of the inverse Compton scattering process and the SSA heating are ignored. The observed flux from a PWN can be expressed as

\[
F_{\nu}^{\text{bl}} = \frac{L_{\nu} \nu^{-\tau_{\nu_c}}}{4\pi D_L^2}, \tag{20}
\]

where \( \tau_{\nu_c} = \sum_{i=1}^{N-1} \Delta t_i = \int R_{\text{max}}^{R_{\text{min}}} \kappa \rho(r) dr \).

### 3 FITTING METHOD

Based on the numerical model developed with section 2, we jointly fit the observations of AT 2017gfo in UV-optical-IR bands and the late-time X-ray observations of GRB 170817A. We implement the Markov Chain Monte Carlo (MCMC) techniques by the use of the Python package emcee (Foreman-Mackey et al. 2013).

The fitting dataset in this work is considered to cover together the AT 2017gfo observations and X-ray observations of GRB 170817A from 300 days to 1234 days after GW170817 trigger. The data of AT 2017gfo have been obtained after the extinction correction\(^1\). In addition, the X-ray data are chosen from Troja et al. (2021) with free photon index \( \Gamma \) at the 0.3 – 10 keV band. It is allowed for the possible presence of

\(^1\) https://kilonova.space/
additional components that may affect the photon index of late observations.

The opacity generated from the bound-free scattering of X-ray photons is much larger than that for UV-optical-IR photons when the PWN photons crossed the ejecta. We consider this effect in detail below. On the one hand, the gray opacity $\kappa_{\text{opt}}$ (ignoring the differences of opacity in different bands) of UV-optical-IR photons is taken as a free parameter, and the optimal result can be obtained by the MCMC method. On the other hand, when calculating the flux of PWN emission at $0.3 - 10$ keV band, the opacity of ejecta is fixed as $\kappa_X(E) = \kappa_0 (\frac{E}{10^3})^{-\beta}$, where $E$ is the energy of X-ray photons, $\kappa_0 = \kappa_X(1\text{keV}) = 7 \times 10^3 \text{ cm}^2 \cdot \text{g}^{-1}$, and $\beta = 1$ is assumed (Chen et al. 2021). Taking into account the variable opacity, the observed flux from PWN at $0.3 - 10$ keV band is calculated by

$$F_{\text{PNW}} = \int_{0.3\text{keV}}^{10\text{keV}} F_X^\text{leak}(E) dE,$$  \hspace{1cm} (21)

Here

$$F_X^\text{leak}(E) = \frac{L_X(E) e^{-\tau_{\text{tot},X}(E)}}{4\pi D_L^2}$$  \hspace{1cm} (22)

is the flux density of leakage after X-ray photons cross the ejecta, where the total optical depth from the ejecta of X-ray photons with energy $E$ is substituted as $\tau_{\text{tot},X}(E) = \int_{R_{\text{min}}}^{R_{\text{max}}} \kappa_X(E) \rho(r) dr$.

Except for the PWN radiation, the external shock emission of the jet have still affect the observations to the remnant of GW170817 event. However, the post-break light curves of GRB 170817A afterglow in different jet models are different based on, for example, the specific jet profile, the consideration of the lateral expansion, and the selection of parameters (e.g., Ren et al. 2020; Lamb et al. 2020; Li & Dai 2021; Hajela et al. 2021a; Troja et al. 2021). It is difficult to proceed with the work if all the models at once are taken into account. Therefore, we choose a phenomenological formula to describe the flux at $0.3 - 10$ keV band of jet emissions,

$$F_{\text{afterglow}} = 120 \cdot t^{-p} \text{erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1},$$  \hspace{1cm} (23)

where $t$ ($>200$ days) is the observed time, and $p = 2.16$ is the spectrum index of electrons in the GRB jet. Here $p$ is chosen from the fits of the early spectra of GRB 170817A afterglow. Thus, the observed total flux $F_{\text{total}}$ at $0.3 - 10$ keV band should be considered by

$$F_{\text{total}} = F_{\text{PNW}} + F_{\text{afterglow}}.$$  \hspace{1cm} (24)

In Ren et al. (2019), the value of the characteristic Lorentz factor of the accelerated leptons in the PWN is fixed to $\gamma_h = 10^4$, and the fraction of the magnetic energy density to the total energy density is fixed to be $\epsilon_B = 10^{-2}$. Both of them are taken to be free parameters in this work. Overall, the eleven physical parameters in our models, $(q_1, q_2, \gamma_0, \epsilon_B, L_{\text{md,0}}, t_{\text{sd}}, M_{\text{ej}}, \kappa_{\text{opt}}, \epsilon_{\text{min}}, \epsilon_{\text{max}}, \delta)$, are fitted as free parameters.

### 4 FITTING RESULT AND DISCUSSION

The model parameters at the $1\sigma$ confidence level are given in Table 1, where the projections of the posterior distribution for the parameters are presented in Figure 1. As shown in Figure 2, the joint fitting shows a good result for the AT 2017gfo observations, and the additional X-ray component formed by the PWN could explain the flattening of the X-ray observations of GRB 170817A.

#### 4.1 Comparison with previous fitting

Comparing the results in this paper and Ren et al. (2019) in Table 1, we find that the optimal values of most of the parameters change slightly. Nonetheless, the spin-down timescale $t_{\text{sd}}$, remains the most important parameter, changing from $2.34 \times 10^5$ s to $3.96 \times 10^5$ s. This change is based on the enlargement of the dataset caused by the addition of X-ray data. Using Equation 6, the newly fitting result of the ellipticity of the central NS can be obtained, $\epsilon = 1.52 \times 10^{-4} I_{55}^{1/2} P_{3,0}^2$, which is slightly less than that of Ren et al. (2019). Meanwhile, the initial spin-down luminosity $L_{\text{md,0}}$ is the same as before, which means the early-time kilonova observations could well estimate the spin-down luminosity of central NS. However, the degeneracy between $t_{\text{sd}}$ and $L_{\text{md,0}}$ also indicates the possibility of the other parameter combinations, as shown in Figure 1. But we note it does not affect the conclusion here.

There is an important change in the parameters of the spectral energy distribution in the PWN. We have gotten the optimal results of $q_1 = 1.85$, $\gamma_0 = 1.66 \times 10^2$, and $q_2 \sim 3$ in this work. Since, in the early fast-cooling stage, the frequencies of most of the PWN photons are located within the range of $\nu_c \leq \nu \leq \nu_b$, the fitting of $q_1$ is determined by the observations of AT 2017gfo, and its changeless result is easy to understand (see Equation 17). We show the evolution of $\nu_b, \nu_c, \nu_a$, and $\nu_{3,0}$ in Figure 3 for the MCMC results. As shown in Figure 3, lines of $\nu_a$ and $\nu_c$ cross each other at $\sim 3000$ days after the merger, and the conversion frequency is located in the X-ray band. One can find that the PWN is still in the fast cooling regime in $\sim 3000$ days after the merger. It means that the constraints on $q_2$ from observations are very weak. This is why $q_2$ is not well constrained, as shown in Figure 1. Based on Equation 17, the photon index of PWN photons is $\Gamma = 1 + q_1/2 = 1.92$, suggests a soft spectrum as seen in the X-ray observations (Troja et al. 2021).

#### 4.2 The trend of X-ray observations

The X-ray afterglow of GRB 170817A is predicted in this work to evolve from flattening to a steep decline, as shown in the left panel of Figure 2. In terms of the trend of X-ray observation, the kilonova ejecta-PWN system model and the BH fallback accretion model (Ishizaki et al. 2021a,b; Metzger & Fernandez 2021) have similar predictions. Nevertheless, there are certain differences in the slope of decay predicted by the two models. The kilonova ejecta-PWN system model has a steeper decay index than that in the BH fallback accretion model, i.e., steeper than $t^{-5/3}$. In addition, the BH fallback accretion model predicts an approximate black-body spectrum of the additional component. However, it is a power-law spectrum for the additional PWN component. Future observations will test our model.

What we should note is that the influence of one or more extra sources on X-ray observations is possible. The models of the kilonova afterglow (Hajela et al. 2021a; Nedora et al. 2021), and even the count-jet (Li et al. 2019; Troja et al. 2021) are predicted to have an impact during this stage. The
combined effect could complicate the evolution of future X-ray observations. To distinguish these components, continuous observations at the radio band is an important approach (see Section 5).

4.3 The radio emission from PWN

We also check the light curves on radio bands emitted by the PWN. The model curves at radio bands shown in Figure 4 are calculated with the MCMC fitting optimal values of the parameters. We find that the PWN’s radio emission flux is below the observations, which verifies the dominance of the GRB afterglow to the observations. Because the late-time radio emission from the PWN is significantly dimmer than the emission from external forward shock of the jet, it is not expected to see an effect of the PWN in future observations.

More signals of binary NS mergers will be detected by GW detectors in near future. Due to the Doppler effect of the large off-axis viewing angle of the merger jet, the prompt GRB radiation is hard to detect for most parts of events. Meanwhile, the afterglows of merger jets are also going to be much dimmer. As shown by our results, however, if a long-lived NS is formed during the binary NS merger, the kilonova ejecta-PWN system could power a long-lasting radio emission. This trait considerably increases the probability of detecting EM counterparts to GW events.

5 CONCLUSIONS

In this paper, we have studied the broadband radiation behavior of the kilonova ejecta-PWN system, and fitted jointly the observations of AT 2017gfo in UV-optical-IR bands and the late-time X-ray observations of GRB 170817A. The kilonova ejecta-PWN system could explain the observations of AT 2017gfo based on two effects, namely the leakage of PWN radiation and its heating influence on the merger ejecta. An additional component shows a signature in the late-time X-ray observations of GRB 170817A when the ejecta is optically thin to X-ray photons from the PWN. We have shown that the trend of future X-ray observations will be dominated by the PWN emission, from flattening to a steep decline, until other sources have their impact, e.g., the kilonova afterglow.

The constrained ranges of the parameters of the central NS in this work, i.e., the dipole magnetic field strength and the ellipticity, are almost the same as those in the previous works (Yu et al. 2018; Ren et al. 2019) and are consistent with the limits set by Ai et al. (2020). It is suggested that a long-lived NS still exists in the merger remnant center a few years after the GW170817 event. Additionally, the new fitting result of the characteristic Lorentz factor of the accelerated leptons indicates that the NS wind is highly magnetized. Note that the parameter values of the PWN are in a reasonable range compared with the PWN observations in our galaxy.

We also showed the light curves of radio emission from the PWN obtained by the optimal values of the fitting parameters. We found that the flux of radio emission from the PWN is lower than the observations of GW170817 event counterpart. This indicates that the radio observations are dominated by the GRB jet afterglow, and not affected by PWN radiation even in the future. This leads to the difference between the kilonova ejecta-PWN system model and the kilonova afterglow model. Besides, the kilonova ejecta-PWN system model and the fallback accretion model have similar predictions of the trend of X-ray observation but certain differences in the slope of decay predicted by the two models. A difference is that the decay index in the kilonova ejecta-PWN system model is steeper than that (e.g., $-5/3$) in the fallback accretion model. In addition, an approximate black-body spectrum of the additional component is suggested by the fallback accretion model but a power-law spectrum is predicted in the kilonova ejecta-PWN system model. Future continuous observations will test our model.

What should be pointed out is that the radio and X-ray emission from the kilonova ejecta-PWN system model could be an important probe of binary NS mergers from days to years after the GW signals. There is a lack of jet-related signals to trigger the detectors when the axis of a merger-produced jet is far away from the line of sight. Differently, the quasi-isotropic, long-existing emission of a kilonova ejecta-PWN system gives rise to more advantage in observations. Its flux is related to the luminosity and total energy released by the central engine. This means that the radiation behavior of a kilonova ejecta-PWN system would directly provide the information of the merger remnant itself, possibly revealing the properties of a newborn NS and an accompanying young PWN.

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DATA AVAILABILITY

The data underlying this paper will be shared on reasonable request to the corresponding authors.

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Table 1. Parameters estimated from the MCMC sampling.

| Parameter                          | Constraint | Range$^1$ | Pervious       |
|------------------------------------|------------|-----------|----------------|
| $\log_{10} L_{\text{mol},0}$ (erg s$^{-1}$) | $41.317^{+0.023}_{-0.023}$ | [39, 43] | $1.85^{+0.85}_{-2.33} \times 10^{41}$ |
| $\log_{10} f_{\text{pol}}$ (s)       | $5.598^{+0.044}_{-0.044}$ | [3, 7]    | $2.34^{+0.57}_{-0.94} \times 10^{5}$ |
| $M_0/0.01M_\odot$                  | $3.044^{+0.033}_{-0.033}$ | [1, 10]   | $3.52^{+0.06}_{-0.11}$ |
| $\kappa_{\text{opt}}$ (cm$^2$ g$^{-1}$) | $1.104^{+0.031}_{-0.028}$ | [0.1, 10] | $1.69^{+0.06}_{-0.09}$ |
| $v_{\text{min}}/c$                  | $0.999^{+0.002}_{-0.002}$ | [0.05, 0.15] | $0.10^{+0.01}_{-0.00}$ |
| $v_{\text{max}}/c$                  | $0.473^{+0.022}_{-0.020}$ | [0.3, 0.6] | $0.34^{+0.01}_{-0.00}$ |
| $\delta$                           | $3.834^{+0.108}_{-0.098}$ | [1, 5]    | $2.47^{+0.02}_{-0.32}$ |
| $q_1$                              | $1.845^{+0.012}_{-0.013}$ | [1, 2]    | $1.83^{+0.02}_{-0.05}$ |
| $q_2$                              | $2.947^{+0.032}_{-0.025}$ | [2, 3]    | $2.25^{+0.10}_{-0.05}$ |
| $\log_{10} \gamma_b$              | $7.221^{+0.045}_{-0.046}$ | [4, 8]    | $10^3$ |
| $\log_{10} \epsilon_B$            | $-1.579^{+0.107}_{-0.064}$ | [-3, -0.5] | $0.01$ |
| $\kappa_X (1\text{keV})$ (cm$^2$ g$^{-1}$) | $7 \times 10^3$ | –         | –              |
| $\alpha$                           | $1$        | –         | 1              |

$^1$ Priors are uniformly distributed.
Figure 1. Posterior probability density contours for the physical parameters from the MCMC sampling.
broadband emission from the KP system

Figure 2. Left Panel: The X-ray light curve of GRB 170817A afterglow with the addition of PWN emission. Data are taken from the free-Γ column, 0.3 – 10 keV flux, in Table 1 of Troja et al. (2021). We also mark the new observation at ~ 1575 days with a star, as given by Hajela et al. (2021c), where the photon index Γ = 1.6 was fixed but the 1σ uncertainties were not reported. We notice the data is consistent with our model. Right Panel: The multiband light curves of AT 2017gfo fitted by our model. The data are taken from https://kilonova.space/ and the extinction correction is performed.
Figure 3. The evolution of $\nu_b$, $\nu_c$, $\nu_a$, and $\nu_M$ of the PWN using the MCMC optimal results. The picture shows that the PWN is in the fast-cooling regime in $\sim 3000$ days after the merger. The transition of $\nu_b$ and $\nu_c$ in the X-ray band will lead to softening of the X-ray spectrum.
Figure 4. Multiband radio light curves emitted from the kilonova ejecta-PWN system of the GW170817 event remnant are calculated by the optimal parameters estimated from the MCMC sampling. The same bands are represented by the same colors correspondingly, where the observational data are described with circles, and the triangles are the upper limits. The data are chosen from Makhathini et al. (2020) and Balasubramanian et al. (2021).

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