Prediction of the second peak in the afterglow of GW170817

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ABSTRACT
We performed calculations of the late radio and X-ray afterglow of GRB/GW170817 in the cocoon-jet paradigm, predicting appearance of a second peak in the afterglow light curve ~ one-three years after the explosion. The model assumes that the prompt emission and early afterglows originate from a cocoon generated during break-out of the delayed magnetically powered jet. As the jet breaks out from the torus-generated wind, a nearly isotropic mildly relativistic outflow is generated; at the same time the primary jet accelerates to high Lorentz factors and avoids detection. As the fast jet slows down, it should become visible to the off-axis observer. Thus, the model has a clear prediction: the X-ray and radio afterglows should first experience a decay, as the cocoon slows down, followed by a rebrightening when the primary jet starts emitting toward an observer.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION
On 2017 August 17, LIGO and Virgo detector discover the gravitational-wave (GW) transient GW170817 (LIGO Scientific Collaboration & Virgo Collaboration 2017), which was consistent with the coalescence of a binary neutron star system. Two seconds later GRB 170817A was registered by GBM/Fermi (Goldstein et al. 2017) and SPI-ACS/INTEGRAL (Savchenko et al. 2017) experiments. A the optical counterpart was detected by a large number of ground-based facilities (Abbott et al. 2017b).

GRB/GW170817 was unusual in many respects. The prompt gamma-ray emission consisted of two distinctive components - a hard short pulse delayed by ~ 2 seconds with respect to the LIGO signal followed by a weaker, softer thermal pulse with 7 ~ 10 keV lasting for another ~ 2 seconds, (see Fig. 1 in Pozanenko et al. (2018)). The appearance of a thermal component at the end of the burst is unusual for short GBRs. Both the hard and the soft components do not satisfy the Amati relation, making GRB 170817A distinctively different from other short GBRs (Pozanenko et al. 2018; Bromberg et al. 2018).

2 MODEL
The detection of the EM signal contemporaneous with gravitational waves is consistent with the binary NS scenario for short GRB (Blinnikov et al. 1984; Paczynski 1986; Eichler et al. 1989). Currently, there are several competing models for the prompt and afterglow emission from GW170817: (i) radially stratified quasi-spherical ejecta (cocoon) traveling at mildly relativistic speeds (e.g., Mooley et al. 2018; Kasliwal et al. 2017; Gottlieb et al. 2018); (ii) emission from off-axis collimated ejecta characterized by a narrow cone of ultra-relativistic material with slower wings extending to larger angles (structured jet) (e.g., Lamb & Kobayashi 2018; Troja et al. 2018b; D’Avanzo et al. 2018; Xie et al. 2018; Margutti et al. 2018; Kathirgamaraju et al. 2017; Lazzati et al. 2017). In the structured jet scenario, the GW170817 merger powered a normal SGRB directed away from the line of sight; (iii) fast jet – cocoon model - we describe it next in more detail.

The key points of the fast jet – cocoon model is described in (Pozanenko et al. 2018); also see Fig 1. An active stage of a merger lasts ~ 10~100 milliseconds after which the neutron stars collapse into BH. During the merger an accretion torus of ~ 0.1M⊙ forms around the BH with a viscous time ~0.1 s (e.g. Ruiz et al. 2016; Perego et al. 2017). At the

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chrotron emission coming from the “break-out” (nearly spherical) part of the mildly relativistic forward shock. But observations up to $t\lesssim250$ days have not been able to distinguish the above scenarios, because of the observed emission will be dominated by radiation from mildly relativistic material (Margutti et al. 2018) present in all the models.

Most importantly, at later times the models predict qualitatively different behaviour. Both the cocoon and structured jet models should produce only one bump in X-ray light curve by the jet or the cocoon. On the other hand, the fast jet – cocoon model (Pozanenko et al. 2018) has two active components - a cocoon formed during jet breakout and an ultra-relativistic jet. The initial rise of x-ray light curve (see red dots Figure 3) is formed by a cocoon - a shock break-out. As we discuss in this paper, later on – a few years after GW event – the fast jet – cocoon model predicts rebrightening of the afterglow as the primary jet slows down and becomes visible (see Fig. 1). The detection of second X-ray or radio bump will be a smoking gun for fast jet – cocoon model and rule out one component models. Calculations of the properties of the predicted second afterglow bump is the key point of the paper.

3 RESULTS

In this work we perform three types of calculations of the predicted second peak: (i) using analytical estimates from (Nakar et al. 2002; Granot et al. 2017, §3.2); (ii) model light curves from the Afterglow library (van Eerten & MacFadyen 2012a, §3.3); (iii) in-house numerical calculations of the synchrotron emissivity of the relativistically expanding and synchrotron cooling plasma, §3.4.

3.1 The fiducial parameters

The accretion torus/disc after the NS-NS merger can be relatively massive $\sim 0.1M_\odot$ (e.g. Perego et al. 2017). The disc produces a dense mildly relativistic wind with mass $\sim 0.05M_\odot$ (Blandford & Begelman 1999; Metzger et al. 2008) and also supplies the central BH with magnetic flux needed to launch the BZ jet. The accretion rate on BH horizon can be estimated as (see more details in Pozanenko et al. 2018)

$$M_{\text{BH}} \approx 0.002 M_\odot \left( \frac{t}{t_0} \right)^{-1} \frac{L}{c^3} M_\odot / s .$$

(1)

Here $M_\odot = 0.1M_{\odot} - 1$ is mass of the disc in solar mass units and time is in seconds. The BZ jet power can be (Blandford & Znajek 1977; Barkov & Komissarov 2008; Barkov & Pozanenko 2011) as high as

$$L_{\text{BZ}} \approx 5 \times 10^{30} \frac{M_{\odot}}{M_\odot} \frac{L}{c^3} \text{erg/s} .$$

(2)

we have assumed efficiency of BZ jet formation $C(a_{\text{BH}}) \approx 1/2$ with BH spin parameter $a_{\text{BH}} = 0.7$ (Ruiz et al. 2016; Radice et al. 2016).

The opening angle of the jet is unknown. The second bump can be detected if jet is relatively narrow and powerful. Following (Pozanenko et al. 2018) the opening angle...
of the jet can be assumed $\theta_j = 0.1 \approx 5^\circ$, so the isotropic jet power can be as high as
\[ E_{\text{iso,max}} \approx \frac{2}{9 \theta_j^2} \int_{t=2}^{t_{\text{max}}} L_{\nu,\text{ tod}} \, dt \approx 10^{53} \text{ ergs.} \] (3)

This is the estimate of the primary jet energy that we will use in the calculations.

Initially, the primary jet emission is beamed away from the observer. As the jet-driven blast wave slows down it becomes visible. In the following, we perform calculations to address the question: What are the conditions required to produce an observable second afterglow bump from the primary jet.

### 3.2 Analytic estimates for detectability of the second peak.

Let us first obtain simple analytic constraints on parameters in order for the second peak associated with the afterglow of the jet to be detectable. We consider the second peak to be detectable if the following 3 criteria are satisfied: 1) The time of the second peak ($t_p\text{peak}$) must be greater than the time of current observations (≈ 250 d), otherwise this peak would have been already detected or can be weaker than the cocoon component, in which case the second peak will not be detectable. 2) The peak flux must be greater than the sensitivity limit of the detector (for radio at 6 GHz we use a limit of 10 $\mu$Jy). 3) The value of the peak flux must be larger than that of the cocoon at the time of the peak. To estimate the flux from the cocoon component at a late time, we use a power law extrapolation of current observations. These criteria are depicted in the top panel of Fig. 2 where the different colors correspond to different values of $\epsilon_B$. Guided by observations (references), we fix the spectral index $\alpha$ and assuming $\theta_{\text{obs}} = 25^\circ$ and $\theta_j = 5^\circ$, $D_L = 40$ Mpc, criterion 2 yields
\[ E_{\text{iso},52} \gtrsim 0.4(n-4) \epsilon_B^{-0.79}. \] (6)

This condition is shown by the dot-dashed line in the bottom panel of Fig. 2, where the different colors correspond to different values of $\epsilon_B = 10^{-2}, 10^{-3}, 10^{-4}$ as indicated in the plot legend. The regions above the dot-dashed lines satisfy criterion 2 for the corresponding values of $\epsilon_B$.

The final criterion for detectability requires that the flux at peak, $F_{\text{peak}}$, is larger than the flux from the cocoon component. The latest observations show GW170817 has started to decline, and this decline follows a power law in time as roughly $\propto t^{-2}$ (Alexander et al. 2018). Attributing this emission to the cocoon, we estimate the late time flux from it by extrapolating this power to later times. For example, taking the 6 GHz measurements we can model the decline in flux as
\[ F_\nu(t) \approx 0.018 \epsilon_B^{-2} \text{ mJy}, \] (7)

with $t$ in days. This extrapolation is shown by the solid line in the top panel of Fig. 2. Criterion 3 requires $F_{\text{peak}} > F_\nu(t_p)$. Using the same parameter substitutions used to obtain equation 6, this condition yields
\[ E_{\text{iso},52} \gtrsim \epsilon_B^{-0.476} n^{-0.0755}. \] (8)

This inequality is shown by the solid lines in the bottom panel of Fig. 2 where different colors correspond to different values of $\epsilon_B$ color coded in the same way as for criterion 2 (the dot-dashed lines). Therefore the inequality is satisfied for regions above the solid lines. So the regions in Fig. 2 which satisfy all three criteria must lie above the dashed black line (criterion 1), and above the dot-dashed and solid lines (criterion 2 and 3) corresponding to the same value of $\epsilon_B$. These regions have been shaded for better visualization. In order for the second peak to be detectable, the parameters pertaining to the jet must lie in the shaded regions.

### 3.3 Second peak light curves using the “Afterglow library”

In this Section we discuss the calculations of the afterglow light curves using the “Afterglow library” (van Eerten & MacFadyen 2012a), which uses linear radiative transfer to calculate synchrotron light curves and spectra. We use a few different sets of parameters when calculating the afterglow (maybe point to a table or plot listing the parameters). Guided by observations (references), we fix the spectral slope, $p = 2.17$ and the observing angle w.r.t jet axis, $\theta_{\text{obs}} = 25^\circ$. We use a typical value of $\epsilon_e = 0.1$, which denotes the fraction of energy in the electrons of the shocked fluid, and a relatively narrow ‘top-hat’ jet with opening angle $\theta_j = 5^\circ$. We vary the isotropic equivalent energy $E_{\text{iso}}$. 

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Where $\theta_{\text{obs}}$ is in degrees and
\[ C(p) = 7440(p - 0.04)\left(\frac{p - 2}{p - 1}\right)^{-1} \left(1.13 \times 10^{-20}\right)^{-p} 10^{-14.96p}. \]

These analytic estimates agree within a factor ~1.5 when compared to the light curves shown in Fig. 3. Criterion 2 requires $F_{\text{peak}}$ to be larger than the detector sensitivity, in the case of radio we use $F_{\text{peak}} \gtrsim 0.01$ mJy. Substituting $\epsilon_e = 0.1$, $p = 2.17$, $\nu = 6$ GHz, $\theta_{\text{obs}} = 25^\circ$, $\theta_j = 5^\circ$, $D_L = 40$ Mpc, criterion 2 yields
\[ E_{\text{iso},52} \gtrsim 0.4(n-4) \epsilon_B^{-0.79}. \]
Figure 2. (Top) Depiction of the three criteria required for detectability of second peak. The plot shows observed radio data (red points) and a power law extrapolation of the observed decline (solid line) (data taken from Margutti et al. 2018; Alexander et al. 2018). Vertical dashed line marks a time of 250 days and dot-dashed horizontal line indicates a radio detectability limit of 10 μJy. The numbered arrows point to the region where the second peak must lie in order to be detectable and the numbers label the criteria described in Section 3.2. In short, 1) requires peak time to be greater than 250d, 2) requires peak flux be above detector sensitivity and 3) requires peak flux be larger than cocoon emission. (Bottom) A figure exploring the parameter space for radio (6 GHz) and X-ray (1 keV). These plots demonstrate the possibility where the afterglow from the jet can cause a late time rise in the light curve of GW170817.

![Figure 2](image_url)

3.4 Emission from off-axis forward shock: numerical calculation of synchrotron emission

Next, we use the classic forward shock model of Sari et al. (1996, 1998) to calculate the emission seen by an off-axis observer. As a novel feature, we calculate numerically the radiative and cooling losses of the particles. To do so, we first find Greens function for particles injected at some moment in time into the forward shock, then we integrate over different injections times, and allowing for time-of-flight delays we calculated the expected light curve.

We assume self-similar relativistic shock with \( \Gamma \propto t^{-m/2} \) with \( m = 3 \) (Blandford & McKee 1976) (thus, we neglect lateral evolution of the shock - it is small, see van Eerten et al. 2010; Lyutikov 2012). The minimum Lorentz factor of accelerated electrons in the shock frame is then

\[
\gamma_{min}' \propto \epsilon_e (\Gamma - 1) \frac{m_p}{m_e}.
\]
while the comoving magnetic field is
\[
\frac{B'^2}{8\pi} = \frac{cB_0^2(G - 1)\Gamma_0\gamma m_p c^2}{t'^2} \propto t'^{-m} \propto t'^{-\frac{2m}{2m+1}}
\]
(primed quantities are in the fluid frame and un-primed are in the coordinate frame.) Thus, the magnetic field strength satisfies
\[
B' = B'_0 \left( \frac{t'}{t'_0} \right)^{-\frac{m}{2m+1}}
\]
where the magnetic field is \( B_0 \) and Lorentz factor is \( \Gamma = \Gamma_0 \) at time \( t' = t'_0 \).

Particles are injected with distribution function \( f_{\text{inj}} \) at time \( t'_i \) through an area \( A \). The Lorentz factor of particles evolves according to
\[
\frac{d\gamma'}{dt'} = -\frac{C_2 B_0^2 \gamma'^2}{t'^{2m+1}} - \frac{m\gamma'}{2\gamma' (2 + m)}
\]
\[
C_2 = \frac{\gamma' t'_0^{2m}}{8\pi m_c}
\]
where the first term describes radiative losses and the second the adiabatic expansion.

The evolution of the distribution function is then described by, first, solving for the Greens function \( G(y', t', t'_i) \)
\[
\frac{\partial G(y', t', t'_i)}{\partial t'} = \frac{C_2 B_0^2 \gamma'^2}{t'^{2m+1}} + \frac{m\gamma'}{2\gamma' (2 + m)} \frac{\partial (\gamma' G(y', t', t'_i))}{\partial y'}
\]
\[
f_{\text{inj}}(y', t'_i) \delta(t' - t'_i)
\]
(13)
with injection
\[
f_{\text{inj}}(y', t'_i) = f'_i(y', t'_i, t'_i) \delta(t' - t'_i)
\]
where \( f'_i \) satisfies \( f'_i \int_{t'_i}^{t'_\text{min}} y'^{-p}dy' = nA_c. \) And, second, integrating with the injection rate
\[
f(y', t') = \int G(y', t', t'_i) f'_i(t'_i)
\]
(15)
where \( f(y', t') \) is the total distribution.

Consider a jet (actually, a shock) with opening angle \( \theta_j \) viewed at an angle \( \theta_{\text{obs}} \). Emissivity at each moment is given by an integral over the shock surface
\[
L'(\omega', t') = \int \int \frac{f(y', t')}{A} P(\omega') dy' dA
\approx \int_{\theta_{\text{obs}}-\theta_j}^{\theta_{\text{obs}}+\theta_j} \int_{\phi_{\min}}^{\phi_{\max}} \int_{\gamma_{\min}}^{\gamma_{\max}} r^2 \sin \theta \frac{f(y', t') P(\omega')}{2\pi (c't')^2 (1 - \cos \theta_j)} dy' d\phi d\theta
\]
\[
= \int_{\theta_{\text{obs}}-\theta_j}^{\theta_{\text{obs}}+\theta_j} \int_{\gamma_{\min}}^{\gamma_{\max}} \left( \phi_{\min} \right)^2 (\phi_{\max} - \phi_{\min}) r^2 \sin \theta f(y', t') P(\omega')
\]
\[
\int_{\gamma_{\min}}^{\gamma_{\max}} \left( \phi_{\max} \right)^2 (1 - \cos \theta_j) dy'
\]
\[
= \int_{\theta_{\text{obs}}-\theta_j}^{\theta_{\text{obs}}+\theta_j} \left( \phi_{\max} \right)^2 \left( \sin \theta_{\text{obs}} \right) \sin \theta dy'
\]
(16)
where \( f \) is the distribution function, \( P_\omega \) is the synchrotron power per unit frequency emitted by each electron and we assumed that \( \theta_{\text{obs}} \) is larger than \( \theta_j \).

The photons emitted by different parts of the jet at the same moment will arrive at different time due to time-of-flight effects. The distance between the initial explosion point and an emission point \( r(\tau, \theta) \) is \( r = v\tau (1 - \beta \cos \theta)^{-1} \), so the surfaces that corresponds to the instantaneous emission have relation:
\[
r = vT_0 \left( \frac{1}{1 - \beta \cos \theta} \right) = \frac{vT_{\text{obs}}}{1 - \beta \cos \theta}
\]
(17)
so far, becomes visible. Using three different approaches – basic analytic estimates, “Afterglow library” and new radiative calculations – we put constrains on the jet energetics and microphysical parameters for the second peak to be observable.

Detectability of the second peak depends on macroscopic parameter (energy of the primary jet $E_{\text{iso}}$ and external density $n$), as well as microscopic parameters ($\epsilon_e$ and $\epsilon_B$), as well as the viewing angle. Observations of the prompt emission and the corresponding GRB constrain the viewing angle to be $20 - 30^\circ$ (e.g. Abbott et al. 2017a; Pozanenko et al. 2018; Alexander et al. 2018). Thus, we are left with $E_{\text{iso}}, n$ and $\epsilon_e, \epsilon_B$.

Our results indicate that even a mildly energetic jet, with $E_{\text{iso}} \sim 10^{51}$ erg may be detected even for low external density $n \sim 10^{-5}$ cm$^{-3}$ (if $\epsilon_e$ and $\epsilon_B$ are not too small). This compares favorably with the expected jet power (3).

We end our conclusions with general remark: if the jet has more energy than the cocoon, it should show up as a second distinct peak. This is because the other parameters ($n, \epsilon_e,$ and $\epsilon_B$) should actually be the same for the 2 afterglow components. In the case of radiatively inefficient jet, the late time emission just tracks the total true energy of the jet. We can even argue that since the jet drives the cocoon, it is typically true that $E_{\text{jet}} > E_{\text{cocoon}}, i.e. we should see two bump structure on light curves from radio through X-ray.

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