Observable Features of GW170817 Kilonova Afterglow

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ABSTRACT

The neutron star merger, GW170817, was followed by an optical-infrared transient (a kilonova) which indicated that a substantial ejection of mass at trans-relativistic velocities occurred during the merger. Modeling of the kilonova is able to constrain the kinetic energy of the ejecta and its characteristic velocity but, not the high-velocity distribution of the ejecta. Yet, this distribution contains crucial information on the merger dynamics. In this work, we assume a power-law distribution of the form $E(>\beta \Gamma) \propto (\beta \Gamma)^{-\alpha}$ for the energy of the kilonova ejecta and calculate the non-thermal signatures produced by the interaction of the ejecta with the ambient gas. We find that ejecta with minimum velocity $\beta_0 \approx 0.3$ and energy $E \sim 10^{51}$ erg, as inferred from kilonova modeling, has a detectable radio, and possibly X-ray, afterglow for a broad range of parameter space. This afterglow component is expected to dominate the observed emission on a timescale of a few years post merger and peak around a decade later. Its light curve can be used to determine properties of the kilonova ejecta and in particular the ejecta velocity distribution $\alpha$, the minimum velocity $\beta_0$ and its total kinetic energy $E$. We also predict that an afterglow rebrightening, that is associated with the kilonova component, will be accompanied by a shift of the centroid of the radio source towards the initial position of the explosion.

Key words: gravitational waves – radiation mechanisms: non-thermal – methods: analytical – gamma-ray burst: individual:170817A

1 INTRODUCTION

The gravitational wave source GW170817 marks the first merger of neutron stars ever detected (Abbott et al. 2017a). A variety of electromagnetic (EM) counterparts were detected following the GW170817 trigger (Abbott et al. 2017b). These counterparts are powered by ejecta and outflows produced from the merger which range from relativistic to non-relativistic velocities. The relativistic outflows are associated with collimated jets, that produce the EM transient known as a gamma-ray burst (GRB). The trans-relativistic and non-relativistic ejecta consists of material that has become unbound during the merger and outflows released by the remnant material following the merger (e.g., disc winds), which powers the transient known as a kilonova (KN; Li & Paczyński 1998; Kulkarni 2005; Rosswog 2005; Metzger et al. 2010).

Both a GRB and KN were detected in GW170817, which, for the first time, directly pointed their origin to NS mergers (e.g., Abbott et al. 2017c; Pozanenko et al. 2018; Goldstein et al. 2017; Soares-Santos et al. 2017; Coulter et al. 2017; Hu et al. 2017; Savchenko et al. 2017; Uteuni et al. 2017). The KN consisted of thermal optical/infrared emission which peaked a few days after the detection of GW170817 and is in general agreement with expectations from KN models (Metzger et al. 2010; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013; Hotokezaka et al. 2018a). The KN is believed to be produced by the radioactive decay of the heaviest elements synthesized in this ejecta. Modeling the multi-wavelength light curves of the KN, one can infer a characteristic ejecta velocity of $\sim 0.1c - 0.3c$ and kinetic energy of $E \sim 10^{51}$ erg (e.g., Cowperthwaite et al. 2017; Nicholl et al. 2017; Arcavi 2018). However, it is not clear how this energy is distributed within the ejecta, which could contain important information on the merger dynamics (e.g., Radice et al. 2018).

The outflows from a NS merger drive an external shock as they propagate through the surrounding medium, this shock accelerates the particles in the external medium causing them to radiate primarily by synchrotron emission. This non-thermal emission associated with the shock is called the afterglow, we will refer to the afterglow associated with the

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jet as the “GRB afterglow” and the afterglow associated with the KN ejecta as the “KN afterglow” in this manuscript.

The GRB including its long term X-ray to radio afterglow that has been detected from GW170817 so far can be explained as originating from a structured jet with a narrow core (with an opening angle of $\sim 2^\circ - 6^\circ$) which is misaligned by $\sim 20^\circ - 30^\circ$ with respect to our line of site (e.g., Alexander et al. 2018; D’Avanzo et al. 2018; Kathirgamaraju et al. 2018b,a; Lamb & Kobayashi 2017; Lazzati et al. 2018; Margutti et al. 2018; Mooley et al. 2018a; Ghirlanda et al. 2018; Troja et al. 2018; Xie et al. 2018; Beniamini et al. 2019). Observation of the rather steep decline of this afterglow after its peak indicates the entire jet has come into view. The jet’s true energy can, therefore, be constrained by the afterglow modeling and is inferred to be $\sim 10^{58}$ erg (e.g., van Eerten et al. 2018), unlike that of other short-duration GRBs (Fong et al. 2015).

In addition to the GRB afterglow, the KN will have its own afterglow. However, the KN ejecta is slower compared to the jet (but has comparable, if not more, energy), which will lead to the KN afterglow peaking at much later times compared to the GRB afterglow (Nakar et al. 2011; Piran et al. 2013; Alexander et al. 2017; Hotokezaka et al. 2018b; Radice et al. 2018). The KN afterglow contains important information on how the energy is distributed within the KN ejecta and its light curve will be sensitive to any velocity stratification within this ejecta. The KN afterglow is the focus of this paper, we will investigate how the KN afterglow differs for a fairly general energy distribution and develop an analytic framework which can be utilized to constrain properties of the KN ejecta using detections (or even non-detections) of the KN afterglow, with an application to GW170817 as an example.

The structure of the paper is the following. Sec. 2 describes our modeling of the KN ejecta, its interaction with the ambient gas, as well as the resulting synchrotron emission from these interactions. In Sec. 3, we apply the KN afterglow model to GW170817, making specific predictions on when this afterglow component could be observed and which ejecta properties can be probed by observations. Sec. 4 summarizes our conclusions.

## 2 THE KN BLAST WAVE AND ITS AFTERTGLOW

During the neutron star merger, a modest fraction of a solar mass is expected to be ejected. The total mass ejected and the angular and velocity distribution of the ejecta depend on the total mass of the progenitor system, the mass ratio of the neutron stars, and the nuclear equation of state (see, e.g., Baiotti & Rezzolla 2017 for a review). In Sec. 2.1, we present a quite general parametrization of the ejecta velocity distribution and proceed to calculate the velocity profile of the shock driven by the ejecta into the ambient gas. Sec. 2.2 focuses on the synchrotron emission from electrons accelerated at this shock.

### 2.1 Properties of the kilonova ejecta and Dynamics of the blast wave

About half a day after the GW170827 trigger, an optical counterpart, AT2017gfo, was discovered (Arcavi et al. 2017; Lipunov et al. 2017; Smartt et al. 2017; Valenti et al. 2017). The observed emission started out blue in color, before rapidly evolving over the following days. Broad spectra at day $\sim 2.5$ post trigger indicate the presence of distinct optical and near infrared emission components. Subsequently, the blue component faded rapidly and the overall spectrum softened, peaking in the near-infrared. The widely accepted interpretation for this emission is the KN model (Cowperthwaite et al. 2017; Chornock et al. 2017; Nicholl et al. 2017; Evans et al. 2017; Abbott et al. 2017b; McCully et al. 2017; Drout et al. 2017; Tanvir et al. 2017). The red KN is likely to be associated with slower ejecta ($\beta \sim 0.1$), while the blue KN can be powered by faster ($\beta \sim 0.3$) ejecta. The former component may have become unbound due to tidal interactions and is predominantly distributed along the equatorial plane while the latter is possibly associated with remnant disk outflows and shock ejected material primarily distributed away from the equatorial plane (Kasen et al. 2015, 2013; Barnes & Kasen 2013; Metzger & Fernández 2014; Perego et al. 2017; Radice et al. 2016; Hotokezaka et al. 2013; Siegel & Metzger 2018; Fernández et al. 2019; see, however, Waxman et al. 2018; Yu et al. 2018 for a different interpretation).

Independent of the details and assumptions involved in the light-curve modeling, the post-merger ejecta appear to be fairly massive with total mass $M \gtrsim 0.05 M_\odot$ and velocity $\sim 0.1-0.3$ c, corresponding to a kinetic energy in excess of $\sim 10^{51}$ erg. These ejecta masses are broadly consistent with the estimated $r$-process production rate required to explain the heavy element abundances of the Universe, providing the first direct evidence that binary neutron star mergers can be a dominant site of $r$-process enrichment (Beniamini et al. 2016b; Kasen et al. 2017; Metzger 2017; Siegel & Metzger 2017; Beniamini et al. 2018; Rosswog et al. 2018; Hotokezaka et al. 2018a).

The modeling of the KN emission is mostly sensitive to the low-end of the velocity distribution of the ejecta$^1$, with which the bulk of the ejecta is moving. Modeling of this thermal transient does not give much information about any high-velocity tail of the ejecta. However, simulations studying NS mergers find that ejecta powering the KN are likely to be broadly distributed in energy as a function of $\beta \Gamma$, where $\Gamma$ is the Lorentz factor of the ejecta (e.g., Hotokezaka et al. 2018b; Fernández et al. 2019; Radice et al. 2018). Motivated by these findings, we assume a power law distribution of the form $E(\beta \Gamma) \propto (\beta \Gamma)^{-\alpha}$ for the energy of the KN blast wave, where $\alpha$ typically varies between 3 to 5. The distribution is normalized to the total energy ($E$) at some minimum velocity ($\beta_0$). Guided by observations of GW170817, we can assume $E(\beta_0 \Gamma_0) = E = 10^{51}$ erg and $\beta_0 = 0.3 (0.1)$ for the fast (slow) component.

The stratified ejecta expands driving a shock into the ambient gas. We assume a uniform external medium and approximate the total energy of the blast wave as $E = (\beta \Gamma)^2 R^3$,

\[ 1 \text{ However, lanthanide-rich materials moving at slower velocities could also be missed in the optical, near infrared as the emission in those bands starts being dominated by the GRB afterglow.} \]
with \( R \) the radius of the blast wave. This expression encapsulates the dynamical evolution of the blast wave during the relativistic (Blandford & McKee 1976) and non-relativistic (Sedov 1959) phases. Given the assumed power law distribution for the ejecta’s kinetic energy \( E \), the blast velocity initially evolves with radius as \( \beta(\Gamma) \propto R^{-\frac{1}{d}} \), where the blast wave is continuously refreshed by slower, more energetic ejecta governed by the power law index \( \alpha \). This continues until the total energy in the shocked external medium is comparable to that of the ejecta, after which point the total energy of the blast wave remains constant (assuming an adiabatic evolution) and the blast velocity evolves as \( \beta(\Gamma) \propto R^{-\frac{1}{d}} \). The radius at which this transition occurs will be called the “deceleration” radius and is given by \( R_{\text{dec}} = (3E_{\text{iso}}/4\pi x_1^2 c^2)^\frac{1}{d} \), where \( m_p \) is the proton mass, \( c \) is the speed of light and \( E_{\text{iso}} \) is the isotropic equivalent energy of the blast wave. The \( R_{\text{dec}} \) corresponds to the deceleration radius of the slowest material (which also carries the majority of the energy).

The isotropic equivalent energy \( E_{\text{iso}} \) of each component is related to the true energy \( E \) by \( E = f_2 E_{\text{iso}} = \frac{1}{2} E_{\text{iso}} \sin \theta \), with \( f_2 \) the solid angle fraction of the blast wave. Employing spherical coordinates, we assume the ejecta is distributed uniformly in the azimuthal direction from \( \phi = 0 \) to \( 2\pi \), and divide the polar extent of the blast wave into two main components. Since the slower, “red” component is likely to be distributed on the equatorial plane, we assume \( \theta = 60^\circ - 120^\circ \) for its polar extent. The fast component (associated with the “blue” KN) is assumed to be distributed within \( \theta = 15^\circ - 60^\circ \) for one hemisphere and \( \theta = 120^\circ - 165^\circ \) for the other hemisphere. Changing the angular extent and viewing angle will not considerably affect our results since bulk of the KN ejecta is not relativistic, making beaming effects modest (see last paragraph of Sec. 2.2 for further details).

### 2.2 Modeling the KN afterglow

The KN blast wave drives a shock through the external medium, energizing the swept up particles and causing them to radiate via synchrotron emission. This emission is termed the afterglow. We assume that the electrons are accelerated into a power-law distribution above a minimum Lorentz factor \( \gamma > \gamma_\text{m} \). The analytic expressions for the radiated flux used or derived below are applicable only if the observing frequency is between the minimum \( (\nu_0) \) and cooling \( (\nu_c) \) frequencies. The plotted light curves, however (which are calculated semi-analytically), include the effects of synchrotron and Compton cooling of the electrons as well as emission during the “deep-Newtonian” phase, applicable when the the minimum Lorentz factor of the electrons \( \gamma_\text{m} \sim 1 \) (Sironi & Giannios 2013).

The KN afterglow emission peaks at the deceleration radius, and the peak flux density can be expressed as (e.g., Nakar & Piran 2011)

\[
F_{\nu,\text{pk}} \approx (115 \mu Jy) \xi_{\text{iso}}^{-1} \beta_0^{-4} \frac{n_0}{\beta_0^5} E_{\text{iso}}^{1/2} d_\text{s}^{-2},
\]

where the prefactor is determined for \( p = 2.2 \), but does not change by more than a factor 3 when \( p \) is varied from 2.1–2.5. Here \( \xi_{\text{iso}} \) and \( \xi_p \) are the fractions of the total energy in the shocked electrons and magnetic fields of the shocked fluid respectively, \( n \) is the number density of the uniform external medium, \( p \) is the power law slope of the distribution of shocked electrons, \( E \) is the true energy (integrated over velocity) of the KN blast wave, \( \nu \) is the observing frequency and \( d \) is the distance to the source. All quantities are in cgs units and we use the notation \( \Omega = Q/10^6 \).

The time of peak can be obtained by relating the observer time to the radius of the blast wave \( (R) \), and substituting \( R = R_{\text{dec}} \) to obtain \( t_{\text{dec}} \approx 10^{-3} \frac{R_{\text{dec}}}{E_{\text{iso}}^{1/2}} (1 + \beta(\rho))^{-1} \). Here we assume the observer is within line of sight of the KN blast wave. The minimum velocity \( (\beta_0) \) is expected to be, at most, mildly relativistic, in this we can assume \( \beta_0 \approx 0.5 \), and obtain an analytic approximation for the observed peak time as

\[
t_{\text{pk}} = t_{\text{dec}} \approx (3.3yr) \left( \frac{E_{\text{iso}}^{1/2}}{n_0^{-1}} \right)^{1/2} \beta_0^{-2} \left( \frac{2 + \alpha}{\beta_0 (5 + \alpha)} - 1 \right)^{1/2}.
\]

As mentioned in Sec. 2.1, \( \alpha \) typically varies between 3 and 5, and will be closely examined in this work. For comparison, we will also consider an extreme case \( \alpha \to \infty \), which corresponds to a single velocity component for the blast wave. For the cases where \( \alpha \) is between 3 and 5, one finds that the peak times vary by less than a factor \( \sim 1.5 \), hence for these cases, we can fix the value of \( \alpha \) (here we will use \( \alpha = 4 \)). Then the peak time can be well approximated by a much simpler form

\[
t_{\text{pk}}(3 \leq \alpha \leq 5) \approx (8.5yr) \left( \frac{E_{\text{iso}}^{1/2}}{n_0^{-1}} \right)^{1/2} \beta_0^{-2} \left( \frac{2}{\beta_0 (5 + \alpha)} - 1 \right)^{1/2}.
\]

When \( \alpha \to \infty \) (corresponding to a single velocity component) the peak time can be approximated as

\[
t_{\text{pk}}(\alpha \to \infty) \approx (22.5yr) \left( \frac{E_{\text{iso}}^{1/2}}{n_0^{-1}} \right)^{1/2} \beta_0^{-2} \left( \frac{2}{\beta_0 (5 + \alpha)} - 1 \right)^{1/2}.
\]

Before the peak (especially at early times of \( \sim 1 \) yr), the blast wave can be mildly relativistic. For these situations the slope of the light curve can be expressed as (Barniol Duran et al. 2015; Katherigamaraju et al. 2016)

\[
s = 3\alpha - 6(p - 1) \frac{2 + \alpha}{8 + \alpha},
\]

where for \( \alpha \to \infty \), we obtain the expected \( \alpha^2 \) rise for associated with a spherical, single velocity component blast wave. Hence, the KN afterglow light curve (before peak) can be expressed as a function of time as

\[
F_{\nu,\text{KN}}(t) = F_{\nu,\text{pk}} \left( \frac{t}{t_{\text{pk}}} \right)^s.
\]
and summing the flux over the entire blast wave while taking into account differences in photon arrival time. These calculations also take into account cooling of the electrons due to synchrotron and self-synchrotron Compton energy losses (e.g., Beniamini et al. 2015), and emission during the deep-Newtonian phase (Sironi & Giannios 2013), with modifications to include an energy distribution in the blast wave as described in Sec. 2.1. Synchrotron self-absorption is not considered in these calculations, which is justifiable since we have verified that the turn-over frequency always lies below the observed bands. This is because the emitting region at \( \sim 1 \) yr after the burst is very extended and thus remains optically thin down to very low frequencies.

The afterglow of the slow component (thin lines in Fig. 1) peaks much later (\( \sim 100 \) yrs) compared to the fast component (\( \sim 10 \) yrs). Therefore, focusing on the current timescale of GW170817, we will restrict our analysis to the radio emission for the remaining panel) since at 1 keV, the spectrum is above the cooling losses (e.g., Beniamini et al. 2015; Fong et al. 2015; Beniamini et al. 2016a; Zhang et al. 2015; Beniamini & van der Horst 2017; Margutti et al. 2018; van Eerten 2018).

Fig. 2 shows KN afterglow of the fast component in radio (3 GHz) and X-ray (1 keV) for different values of \( \alpha \) with the "typical" parameters mentioned above. In the same plot we show observed data points for the afterglow of GRB170817A (data obtained from Hallinan et al. 2017; Alexander et al. 2018; Margutti et al. 2018; Mooley et al. 2018b) along with the theoretical prediction of the afterglow from the structured jet model presented in Kathirgamaraju et al. (2018a). The KN afterglow light curves are produced semi-analytically following the same method as detailed in Sec. 2.

Equation 6 accurately reproduces the radio afterglow shown in the top panel of Fig. 2 before peak. However, this equation does not apply to the X-ray afterglow (bottom panel) since at 1 keV, the spectrum is above the cooling frequency for the timescales shown and parameters chosen. It might be more difficult to detect the KN afterglow in the X-ray band if it is in the fast cooling regime, therefore, we will focus our analysis on the radio emission for the remainder of this work. An X-ray detection of the KN afterglow, for more favorable parameters than our reference case, is however possible.

Fig. 2 and equation 5 show that observations of the rise in the afterglow can be used to constrain \( \alpha \) well before the peak (provided \( p \) is known, e.g., from multi-frequency observations). The peak time and flux can be used to constrain quantities such as \( \beta_0 \) and \( E \). However, as we show below, even a non-detection of the KN afterglow can be used to constrain properties of the KN outflow.

We have observed the peak in the afterglow of GRB170817A at \( \sim 150 \) days, and the decline post-peak follows a power law in time with slope \( \sim -2.4 \) (Alexander et al. 2018; Mooley et al. 2018b). Therefore, the decline of the

3 APPLICATION TO GW170817

In this section we apply our KN afterglow model to GW170817 as an example case, with focus on how properties of the ejecta can be constrained using detections (or even a non-detection) of the KN afterglow emission. In Sec 3.1, we present general expressions with the prediction of the afterglow flattening/rebrigheting associated with the emergence of the KN afterglow, and summarize what we can learn from this emergence. Sec. 3.2 focuses on the much smaller parameter space of the model for which one can fit the observed GRB afterglow with a structured jet model. In this case, our predictions for the expected emission from KN component become much more definite.

3.1 Constraining the KN of GW170817

In order to produce example light curves for the KN afterglow, we have to assume some values for the microphysical parameters (\( \epsilon_e, \epsilon_B, \) particle index (\( p \)), and the external density (\( n \)). As a guide for our choice, we use typical parameters inferred from the fitting and observations of GRB170817A afterglow (associated with the jet), as well as typical parameters inferred for other afterglows of short GRBs, which are, \( \epsilon_e = 0.1, \epsilon_B = 10^{-3}, n = 10^{-5} \text{ cm}^{-3}, p = 2.2 \) (Nava et al. 2014; Santana et al. 2014; Granot & van der Horst 2014; Beniamini et al. 2015; Fang et al. 2015; Beniamini et al. 2016a; Zhang et al. 2015; Beniamini & van der Horst 2017; Margutti et al. 2018; van Eerten 2018).

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GRB afterglow can be modelled as

\[ F_\nu(t) \approx (100 \, \mu\text{Jy}) \left( \frac{t}{0.44 \, \text{yr}} \right)^{-2.4}. \]  

(7)

By equating 6 and 7, we can find the time at which the flux from the afterglow and KN will be equal \( (t_{eq}) \). After this time, it will be possible to detect the KN afterglow. The general expression for \( t_{eq} \) is

\[ t_{eq} = \frac{(100 \, \mu\text{Jy})(0.44\,\text{yr})^{2.4} \nu^{2.4} \beta_d^{5.5}}{F_{\nu,p}} \left( \frac{14 \, \beta_d \nu^{2.4}}{F_{\nu,p}} \right)^{-\frac{1}{2.4}}. \]  

(8)

For \( 3 \leq \alpha \leq 5 \), we can substitute expression 3 for \( t_p \) and obtain

\[ t_{eq} \approx \frac{0.2 (8.3) \beta_d^{5.5}}{f_B E_\text{iso,51} \nu^{2.4} \beta_0^{1.5}} \left( \frac{\nu^{2.4}}{\beta_d} \right)^{-\frac{1}{2.4}} \beta_0^{0.5} \approx \frac{\beta_d^{5.5}}{f_B E_\text{iso,51} \nu^{2.4} \beta_0^{1.5}} \left( \frac{\nu^{2.4}}{\beta_d} \right)^{-\frac{1}{2.4}} \beta_0^{0.5}, \]  

(9)

where we have substituted \( d = 40 \) Mpc for the distance to the source. If we substitute \( \alpha = 4 \) and \( p = 2.2 \) for example,

\[ t_{eq} \approx \frac{\beta_d^{5.5}}{f_B E_\text{iso,51} \nu^{2.4} \beta_0^{1.5}} \left( \frac{\nu^{2.4}}{\beta_d} \right)^{-\frac{1}{2.4}} \beta_0^{0.5}. \]

Figure 2. A predicted rebrightening in the GW170817 afterglow. Observed data of GRB170817A afterglow (points) along with the afterglow model from (Kathirgamaraju et al. 2018a) (dashed lines) in radio (top panel) and X-ray (bottom panel). Solid lines show KN afterglow light curves for varying \( \alpha \) (see insert labels), which peak at later times resulting in a flattening/rebrightening in the overall afterglow. The X-ray afterglow of the KN is above the cooling frequency for the times considered here. Therefore, detection in the radio is more favourable. Data points obtained from Hallinan et al. (2017); Alexander et al. (2018); Margutti et al. (2018); Mooley et al. (2018b).

For \( \alpha = 3 \) and \( \alpha = 4 \), we can substitute \( t_{eq} \) from equation 9 for minimum speed of the KN blast wave \( (\beta_0) \) vs. external density \( (n) \) fixing \( \alpha = 3 \) (top panel), \( \alpha = 4 \) (middle panel) and \( \alpha = 5 \) (bottom panel). The solid and dashed lines show the \( t_{eq} = 1 \) yr and \( t_{eq} = 2 \) yr contours respectively. The peak of the KN afterglow in the gray, shaded region lies below the detectability limit \( (F_{\nu,p} = 5 \mu\text{Jy}) \) in radio and therefore is not detectable. Horizontal, dot-dashed line marks \( \beta_0 = 0.3 \) which is the typical velocity of the fast component inferred from observations of the blue KN. The emergence of the KN afterglow has not been detected yet implying \( t_{eq} \gtrsim 1 \) yr, which corresponds to regions below the \( t_{eq} = 1 \) contour in the above figures.

Figure 3. Contour plot of the time of emergence of the KN afterglow \( t_{eq} \) (equation 9) for minimum speed of the KN blast wave \( (\beta_0) \) vs. external density \( (n) \) fixing \( \alpha = 3 \) (top panel), \( \alpha = 4 \) (middle panel) and \( \alpha = 5 \) (bottom panel). The solid and dashed lines show the \( t_{eq} = 1 \) yr and \( t_{eq} = 2 \) yr contours respectively. The peak of the KN afterglow in the gray, shaded region lies below the detectability limit \( (F_{\nu,p} = 5 \mu\text{Jy}) \) in radio and therefore is not detectable. Horizontal, dot-dashed line marks \( \beta_0 = 0.3 \) which is the typical velocity of the fast component inferred from observations of the blue KN. The emergence of the KN afterglow has not been detected yet implying \( t_{eq} \gtrsim 1 \) yr, which corresponds to regions below the \( t_{eq} = 1 \) contour in the above figures.
t\eq becomes

\[ t_{\text{eq}} \approx (2\text{yr}) n^{-0.2} \beta_0^{-0.5} \epsilon_5^{0.31} v_9^{0.21} e_1^{-0.43} \epsilon_{B,-3}^{-0.29} \epsilon_{\nu}^{-0.36} . \]  

(10)

Fig. 3 shows a contour plot of \( t_{\text{eq}} \) for \( \beta_0 \) vs \( n \) where each panel corresponds to a different value of \( \alpha \). The rest of the parameters used are \( \epsilon_5 = 0.1, \epsilon_B = 10^{-3}, E_{150} = 10^{51} \text{erg}, p = 2.2 \), and \( \nu = 3 \text{ GHz} \).

The rebrightening time \( t_{\text{eq}} \) can also be calculated for \( \alpha \to \infty \) case using equation 4. We do not focus on this case here since after the afterglow at \( t_{\text{eq}} \) will most likely be too faint to detect (see Fig. 2). However, the peak of the KN afterglow may still be bright enough to be detected. Interestingly, therefore, if the KN ejecta are characterized by a very steep velocity profile, its afterglow emission could fall below detectability limits in the near future, only to re-emerge several years, or even a decade, later.

We have not yet observed the emergence of the KN afterglow in GW170817, indicating that \( t_{\text{eq}} \) must be greater than the current observing time \( t_{\text{eq}} > 1 \text{ yr} \). Using this condition on \( t_{\text{eq}} \), we can place some constraints on the dynamical and micro-physical quantities related to the KN afterglow (such as \( \beta_0 \) and \( \alpha \)) even without a detection. For example, if we substitute \( \epsilon_5 = 0.1, E_{150} = 10^{51} \text{erg}, p = 2.2, \alpha = 4 \), and \( \nu = 3 \text{ GHz} \), the condition \( t_{\text{eq}} \geq 1 \text{ yr} \) yields

\[ \beta_0 \lesssim 0.25 n^{-0.33} \epsilon_{B,-3}^{0.28} . \]  

(11)

This equality \( t_{\text{eq}} = 1 \text{ yr} \) is shown by the solid, white lines in Fig. 3 (with \( \epsilon_B = 10^{-3} \)). For regions above the \( t_{\text{eq}} = 1 \text{ yr} \) contour, \( t_{\text{eq}} \) is less than 1 yr, which means these regions are excluded since no rebrightening flattening has been observed in the afterglow of GW170817. For comparison, Fig. 3 also shows the \( t_{\text{eq}} = 2 \text{ yr} \) contour. In order for the KN afterglow to be detectable, at the very least, its peak flux must be greater than sensitivity limits of detectors. For radio observations, we will use a sensitivity limit 5\( \mu \text{Jy} \) so that the detectability condition is \( F_{\nu} \geq 5 \mu \text{Jy} \), with \( F_{\nu} \) given in equation 11. Substituting the same parameters used to obtain 11, this detectability condition yields

\[ \beta_0 \gtrsim 0.08 n^{-0.34} \epsilon_{B,-3}^{0.4} . \]  

(12)

Regions which do not satisfy this condition are shaded gray in Fig. 3 (using \( \epsilon_B = 10^{-3} \)) and the KN afterglow will not be detectable for parameters in this region. The horizontal dotted line marks where \( \beta_0 = 0.3 \), which is the characteristic velocity inferred from observations of the blue KN (see Sec. 2). The range of densities for the \( x \)-axis of Fig. 3 was chosen guided by afterglow modelings of GW170817 (Lazzati et al. 2018; van Eerten et al. 2018; Resmi et al. 2018; Wu & MacFadyen 2018). From these conditions, we can begin to constrain properties of the KN. For example, from Fig. 3, we see that for \( \alpha = 3 \) (top panel), if \( \beta_0 = 0.3 \), the external density must be \( \lesssim 0.005 \text{ cm}^{-3} \), otherwise the KN afterglow would have been detected by now.

### 3.2 Combined Constraints from the jet afterglow

Using the analytic expressions given in Sec. 2 the analysis carried out in Sec. 3 can be done for different values of micro-physical parameters \( (\epsilon_5 \text{ and } \epsilon_B) \) and external density \( n \), provided that the observed frequency lies between \( v_9 \) and \( v_{c} \) for the choice of parameters. In this example (Fig. 2), values that provide a good fit for the afterglow observations of GRB170817A were used. The typical values of density and \( \epsilon_B \) found from fitting the GRB afterglow of GW170817 range from \( \sim 10^{-3} - 10^{-1} \text{ cm}^{-3} \) and \( \sim 10^{-5} - 10^{-3} \text{ respective} \) (e.g., Resmi et al. 2018; van Eerten et al. 2018; Wu & MacFadyen 2018), where higher densities require lower values of \( \epsilon_B \) to fit the afterglow (see e.g., Fig. 3 of Wu & MacFadyen 2018). This inverse proportionality becomes evident if one uses the expression for the peak flux of a GRB afterglow (e.g., Nakar et al. 2002) and expresses \( \epsilon \) in terms of \( \epsilon_B \) (keeping other parameters fixed) to find \( n \approx \epsilon_B^{-1} \) (this is also the case for the peak of the KN afterglow; equation 1).

Fig. 4 shows the radio afterglow light curves of the KN for these range of densities and \( \epsilon_B \) to demonstrate how the light curves would vary for different choices of these parameters which provide reasonable fits for the GRB afterglow. Fig. 4 shows that within this range (that spans 2 orders of magnitude), the flux density of the afterglow does not change by more than a factor \( \sim 2 \) when compared to our example case of \( n = 10^{-2} \text{ cm}^{-3} \) and \( \epsilon_B = 10^{-3} \) (see Fig. 4). Which means our conclusions will remain the same for this broad range.
GW170817 Kilonova afterglow

4 DISCUSSION/CONCLUSIONS

GW170817 was followed by an optical-IR transient, AT2017gfo, which revealed that the merger was accompanied by a substantial ejection of mass $M_\text{ej} \sim 0.05M_\odot$ at trans-relativistic velocities $\beta_0 \sim 0.1–0.3$. The KN modeling is able to constrain the kinetic energy of the ejecta and its characteristic velocity but is less sensitive to the high-velocity distribution of the ejecta. Yet, this distribution contains crucial information on the merger dynamics. In this work, we assume a power-law distribution of the form $E(\beta) \propto (\beta \Gamma)^{-\alpha}$ for the energy of the KN ejecta and calculate the resulting afterglow powered by the KN ejecta. We find that:

(i) A fast KN component with minimum velocity $\beta_0 \approx 0.3$ and energy $E \approx 10^{51}$ erg, which is likely responsible for the observed blue KN emission, can produce a detectable radio, and possibly X-ray, afterglow for a broad range of the parameter space.

(ii) For $3 \lesssim \alpha \lesssim 6$, the KN afterglow is expected to emerge, by dominating the afterglow emission, on a timescale of a few years and peak around a decade later.

(iii) For steep values of $\alpha \to \infty$, the afterglow emission can drop below detectability levels before the KN afterglow emerges on a decade time scale.

(iv) The time of emergence $t_\text{eq}$ (equation 8), the rise slope of the light curve $s$ (equation 5) and the peak time $t_p$ (equation 2) can be used to determine properties of the KN ejecta, in particular, the ejecta velocity distribution $\alpha$, the minimum velocity $\beta_0$, and its kinetic energy $E$.

The GRB afterglow of GW170817 has been characterized by a superluminal apparent speed in the radio (Mooley et al. 2018a). This finding is consistent with the misaligned jet interpretation used to describe the non-thermal emission observed so far from this event (see also Zrake et al. 2018 for an investigation into the radio map of GW170817). On the other hand, the KN blast is expected to quasi isotropic with its radio image centered around the merger location. We, therefore, predict that any afterglow rebrightening –marking the emergence of the KN component– will be accompanied by a shift of the centroid of the radio towards the initial position of the explosion. Ultimately, the KN afterglow may be sufficiently bright and extended for the source to be resolved, Fig. 5 shows the size of the source vs. time with $n = 10^{-2}$ cm$^{-3}$ and $E = 10^{51}$ erg. The size is obtained by calculating the extent of the blast wave which contributes to half of the afterglow emission and projecting this extent perpendicular to the line of sight. For $\beta_0 \approx 0.3$, the typical size of the source is $\sim 10$ mas at around twenty years post merger.

As of the time of writing of this work, the afterglow emission from GW170817 is declining quite steeply (Mooley et al. 2018b), which is expected from a structured jet model that is moderately misaligned with respect to our line of sight (e.g., Kumar & Granot 2003; Salmonson 2003; Kathirgamaraju et al. 2018a; Lamb & Kobayashi 2018; van Eerten et al. 2018; Beniamini & Nakar 2019). We find here that the ejecta responsible for the KN may cause the afterglow light curve to rebrighten in the near future and be detectable for decades to come.

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