THE ELECTROMAGNETIC COUNTERPART OF THE BINARY NEUTRON STAR MERGER LIGO/VIRGO GW170817.
V. RISING X-RAY EMISSION FROM AN OFF-AXIS JET

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Abstract

We report the discovery of rising X-ray emission from the binary neutron star (BNS) merger event GW170817. This is the first detection of X-ray emission from a gravitational-wave source. Observations acquired with the Chandra X-ray Observatory (CXO) at $t \approx 2.3$ days post merger reveal no significant emission, with $L_x \lesssim 3.2 \times 10^{38}$ erg s$^{-1}$ (isotropic-equivalent). Continued monitoring revealed the presence of an X-ray source that brightened with time, reaching $L_x \approx 9 \times 10^{39}$ erg s$^{-1}$ at $t \approx 15.1$ days post merger. We interpret these findings in the context of isotropic and collimated relativistic outflows (both on- and off-axis). We find that the broad-band X-ray to radio observations are consistent with emission from a relativistic jet with kinetic energy $E_k \sim 10^{49}$ erg, viewed off-axis with $\theta_{\text{obs}} \sim 20-40^\circ$. Our models favor a circumbinary density $n \sim 10^{-4}$–$10^{-3}$ cm$^{-3}$, depending on the value of the microphysical parameter $\epsilon_B = 10^{-4}$–$10^{-2}$. A central-engine origin of the X-ray emission is unlikely. Future X-ray observations at $t \gtrsim 100$ days, when the target will be observable again with the CXO, will provide additional constraints to solve the model degeneracies and test our predictions. Our inferences on $\theta_{\text{obs}}$ are testable with gravitational wave information on GW170817 from Advanced LIGO/Virgo on the binary inclination.

Subject headings: GW

1. INTRODUCTION

Gravitational waves (GW) from the merger of a binary neutron star (BNS) system were detected for the first time by Advanced LIGO and Advanced Virgo on 2017 August 17.53 UT (LV Scientific Collaboration [2017] Abbott et al. [2017]). The GW event, named GW170817, was localized to a region of $\sim 30$ deg$^2$ with a distance of $\sim 40$ Mpc. The GW signal from the BNS merger was closely followed in time by a short burst of $\gamma$-ray emission detected by Fermi and Integral.

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16 Note that the optical transient source was given the name of SSS17a (Coulter et al. [2017b], and DLT17ck (Yang et al. [2017]), and Soares-Santos et al. [2017] as well as an International Astronomical Union name of AT2017gfo.
the X-ray emission, and place constraints on the properties of the circumbinary medium, jet energetics, collimation and observer angle based on the broad-band X-ray to radio observations. A comparison to the properties of “canonical” SGRBs can be found in Fong et al. (2017a), while we refer to our companion paper Alexander et al. (2017) for a dedicated discussion of the radio observations of GW170817. Our X-ray observations of NGC 4993, the host galaxy of GW170817, are discussed in Blanchard et al. (2017).

We assume a distance to NGC 4993 of 39.5 Mpc (z = 0.00973) as listed in the NASA Extragalactic Database. 1σ c.l. uncertainties are listed unless otherwise stated. In this manuscript we employ the notation $Q_\gamma = Q/10^{15}$. In this paper we always refer to isotropic-equivalent luminosities. We differentiate between isotropic-equivalent kinetic energy $E_{k,iso}$, and beaming-corrected kinetic energy of the blast wave $E_b$, where $E_b = E_{k,iso}(1-\cos(\theta_j))$ and $\theta_j$ is the jet opening angle.

2. OBSERVATIONS

With the Dark Energy Camera, we independently discovered and localized the optical transient to RA=13°09′48.08″, Dec=–23°22′53.32″ (J2000) with 1σ uncertainties of 130 mas and 60 mas, respectively (Soares-Santos et al. 2017), and initiated multi-wavelength follow up of the transient across the electromagnetic spectrum. Here we report on X-ray observations that led to the first identification of rising X-ray emission from a binary neutron star merger event GW170817.

2.1. Swift X-ray Observations

The Swift spacecraft (Gehrels et al. 2004) started observations of the optical counterpart of LIGO/Virgo GW170817 (Coulter et al. 2017b,a; Allam et al. 2017; Soares-Santos et al. 2017; Yang et al. 2017) with the X-ray telescope (XRT; Burrows et al. 2005) on August 18th, 03:33:33 UT, 14.9 hours after the GW trigger. Swift-XRT observations span the time range 0.6–11.5 days since trigger, at which point the target entered into Sun constraint. Swift-XRT data have been analyzed using HEASOFT (v6.22) and corresponding calibration files, employing standard filtering criteria and following standard procedures (see Margutti et al. 2013 for details). No transient X-ray emission is detected at the location of the GW optical counterpart (Evans et al. 2017b; Cenko et al. 2017; Evans et al. 2017a), with typical count-rate limits of a few $10^{-3}$ cps. The neutral Hydrogen column density in the direction of the transient is $N_{\text{H}}^n = 0.0784 \times 10^{22}$ cm$^{-2}$ (Kalberla et al. 2005).

For a typical absorbed power-law spectrum with photon index $\Gamma \sim 2$ and negligible intrinsic absorption (see below), the corresponding 3σ flux limit is $\sim 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ (unabsorbed). L$_b < 4 \times 10^{40}$ erg s$^{-1}$ at the distance of 39.5 Mpc. As we show in detail in Fong et al. (2017a), Swift-XRT observations constrain the X-ray emission associated with the optical counterpart of LIGO/Virgo GW170817 to be significantly fainter than cosmological short GRBs at the same epoch (Margutti et al. 2013; Fong et al. 2015; D’Avanzo et al. 2014).

2.2. Chandra X-ray Observations

We initiated deep X-ray follow up of the optical transient with the Chandra X-ray Observatory (CXO) on 2017 August 19.71 UT, $\delta t \approx 2.3$ d after the GW detection (observation ID 18955; PI: Fong; Program 18400052). Chandra ACIS-S data have been reduced with the CIAO software package (v4.9) and relative calibration files, applying standard ACIS data filtering. Using wavdetect we find no evidence for X-ray emission at the position of the optical transient (Margutti et al. 2017) and we infer a 3σ limit of $1.2 \times 10^{-4}$ cps (0.5-8 keV energy range, total exposure time of 24.6 ks). For an assumed absorbed spectral power-law model with $\Gamma = 2$, negligible intrinsic absorption and $N_{\text{H}}^\text{int} = 0.0784 \times 10^{22}$ cm$^{-2}$, the corresponding absorbed (unabsorbed) flux limit in the 0.3-10 keV energy range is $F_\delta < 1.4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ ($F_\delta < 1.7 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$). The luminosity limit is $L_\delta < 3.2 \times 10^{38}$ erg s$^{-1}$ (0.3-10 keV), making the X-ray counterpart to GW170817 $\geq 1000$ times fainter than on-axis short GRBs at the same epoch (Fong et al. 2017a).

We re-visited the location of the optical transient on September 1.64 UT (starting 15.1 days since trigger) under a DDT program with shared data (observation ID 20728; data shared among Troja, Haggard, Margutti; Program 18508587) with an effective exposure time of 46.7 ks. An X-ray source is blindly detected (Fong et al. 2017b) with high significance ($\sim 7.3 \sigma$ at RA=13°09′48.076″ and Dec=–23°22′53.34″ (J2000), see Fig. 1) consistent with the optical transient and the findings by Troja et al. (2017).

The source 0.5-8 keV count-rate is $(3.8 \pm 0.9) \times 10^{-4}$ cps. The total number of 0.5-8 keV counts in the source region is 19. Based on Poissonian statistics, the probability to observe 0 events in 24.6 ks (as in our first observation), if the expected rate is 19 events in 46.7 ks, is $\approx 0.0045%$ (≈ 4 Gaussian σ equivalent). A similar result is obtained with a Binomial test ($P \approx 0.03%$, corresponding to $\sim 3.6$ Gaussian σ). We can thus reject the hypothesis of a random fluctuation of a persistent X-ray source with high confidence, and we conclude that we detected rising X-ray emission in association to the optical counterpart to GW170817.

The limited statistics does not allow us to constrain the spectral model. We employ Cash statistics to fit the spectrum with an absorbed power-law spectral model with index $\Gamma$ and perform a series of MCMC simulations to constrain the spectral parameters. We find $\Gamma = 1.6^{+0.5}_{-0.2}$ (1σ c.l.) with no evidence for intrinsic neutral hydrogen absorption $N_{\text{H}}^\text{int} < 3 \times 10^{22}$ cm$^{-2}$ (3σ c.l.). For these parameters, the inferred 0.3-10 keV flux is $(3.0-5.6) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ (1σ c.l.). The corresponding unabsorbed flux is $(3.1-5.8) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, luminosity $L_\delta$ in the range $(5.9-11.1) \times 10^{38}$ erg s$^{-1}$ cm$^{-2}$ (1σ c.l.).

Figure 2 shows our CXO light-curve of the X-ray source associated with GW170817. In this figure we add the X-ray measurement by Haggard et al. (2017a) obtained 15.9 days after GW trigger (PT Haggard; ID 18988) and rescaled to $\Gamma = 2$ in the 0.3-10 keV energy range, leading to $F_\delta \sim 4.5 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. This flux is consistent with our observations obtained $\sim 24$ hrs before, with no statistically significant evidence for temporal variability of the source on this timescale. An estimate of the lower limit of the X-ray flux

\[ F_{\delta,\text{lim}} \leq 1.32 \times 10^{-4} \mu Jy. \]

17 Significant intrinsic absorption is not expected, given the early-type nature of the host galaxy and the location of the transient in the outskirts of its host galaxy. Blanchard et al. (2017) This expectation is independently confirmed by our optical/NIR modeling (Blanchard et al. 2017), which indicates $N_{\text{H}}^\text{int} < 10^{21}$ cm$^{-2}$, and by the X-ray analysis of the epoch when the transient is detected. However, we repeated our analysis of the first CXO epoch focusing on the harder part of the spectrum to minimize the possible effects of absorption. We find a 3σ limit of $1.2 \times 10^{-4}$ cps (0.8-8 keV), which corresponds to a limit on the flux density at 1 keV $F_{\delta,1keV} < 1.40 \times 10^{-4} \mu Jy$. With the previous spectral calibration we would infer a similar value $F_{\delta,1keV} < 1.32 \times 10^{-4} \mu Jy$. We conclude that our modeling below, which employs $F_{\delta,1keV}$ is thus robust.
at \( t \sim 10 \) days, corresponding to the reported detection of X-ray emission with the CXO using an exposure time of 50 ks (Troja et al. 2017) is also shown to guide the eye.

3. ORIGIN OF THE RISING X-RAY EMISSION

We discuss the physical origin of the rising X-ray emission found in association to GW170817 considering the following observational constraints: (i) The peak of the X-ray emission is at \( t_{pk} \geq 15 \) days; (ii) The X-ray light-curve shows mild temporal evolution, with no signs of rise or decay over a \( \sim 24 \) hr timescale at \( t \sim 15 \) days; (iii) The blue colors of the early kilonova emission (Cowperthwaite et al. 2017; Nicholl et al. 2017) suggest \( \theta_{obs} < 45^\circ \) (Sekiguchi et al. 2016), where \( \theta_{obs} \) is the observer angle with respect to the jet axis (Sec. 3.2); (iv) Simultaneous radio observations from Alexander et al. (2017a) which include the earliest radio observations of this transient at different frequencies and detections at 6 GHz. Below we discuss the nature of the X-ray emission from GW170817 considering this entire range of observational constraints available at the time of writing.

3.1. Constraints on on-axis outflows

We first consider constraints on on-axis\(^{18}\) relativistic outflows (collimated or not collimated), under the assumption that the blast wave has transferred to the ISM most of its energy by the time of our first CXO observation, and its hydrodynamics is thus well described by the Blandford-McKee (BM) self-similar deceleration solution (Blandford & McKee 1976). Electrons are accelerated at the shock front into a power-law distribution \( N(\gamma) \propto \gamma^{-p} \) for \( \gamma \geq \gamma_{min} \) and cool through synchrotron emission and adiabatic losses.

In the standard synchrotron model (e.g. Granot & Sari 2002), the flux density \( F_{\nu} \propto n^{1/2}E_{k,iso}^{(3-p)/4}e_p^{-1}e_B^{-(p-3)/4}\) if the X-rays are on the \( \nu^{(1-p)/2} \) spectral segment (i.e. \( \nu_s < \nu_c \)) and \( F_{\nu} \propto E_{k,iso}^{(2+p)/4}e_p^{-1}(\nu_c/\nu)^{(p-2)/4}\) if the X-rays are on the \( \nu^{-p/2} \) spectral segment (\( \nu_s > \nu_c \)). \( \nu_c \) is the synchrotron cooling frequency (e.g. Rybicki & Lightman 1979), \( e_p \) and \( e_B \) are the post-shock energy fractions in electrons and magnetic field, respectively and \( n \) is the ISM density. We use a constant density medium as expected for a non-massive star progenitor.

Within this model, and for fiducial parameters \( e_p = 0.1 \), \( e_B = 0.01 \) and \( p = 2.4 \) set by median value of cosmological short GRBs (Fong et al. 2015), the deep CXO non-detection on day 2.34 constrains \( E_{k,iso} \leq 10^{47}n_0^{-10/27} \) erg for \( \nu_s < \nu_c \) and \( E_{k,iso} \leq 4 \times 10^{46} \) erg for \( \nu_s > \nu_c \). \( n_0 \) is the circumburst density in units of \( cm^{-3} \). Consistent with the results from radio observations (Alexander et al. 2017a), this analysis points at low \( E_{k,iso} \leq 10^{49} \) erg for the range of densities \( n \sim (3 - 15) \times 10^{-3} \) cm\(^{-3} \) associated to cosmological short GRBs, which are characterized by \( E_{k,iso} \sim (1 - 3) \times 10^{51} \) erg for the same microphysical parameters \( e_p = 0.1 \) and \( e_B = 0.01 \) (Fong et al. 2015). We note that this conclusion does not depend on the choice of \( p \), with \( p = 2.1 - 2.4 (p > 2.4 \) violates our radio limits). This solution is only valid during the relativistic phase at \( t < t_{SR} \) (where \( t_{SR} \sim 1100(E_{k,iso}/10^{53} \text{erg})^{1/3} \) days, Piran 2004) and constraints the presence of an undetected, temporally decaying X-ray emission at \( t < 2.34 \) days, with properties that are clearly distinguishable from cosmological short GRBs seen on-axis (Fong et al. 2017a).

A rising X-ray light-curve can be the result of a delayed onset of the afterglow emission, as the blast wave decelerates into the environment and transfers energy to the circumburst medium. In this scenario, the initial Lorentz factor of the outflow is \( \Gamma_0 \sim 8.0E_{k,iso,52}^{1/8}n_0^{-1/8} \) (Fong et al. 2017a) where \( T_{pk,day} \) is the peak time of the afterglow in days (Sari & Piran 1999). A distinguishing feature of the early afterglow emission is an initial very steep rise of the emission \( \propto t^2 \) or \( \propto t^{11/3} \) (Sari & Piran 1999). The stable X-ray flux of the source at \( t \sim 15 - 30 \) days suggests that \( T_{pk,day} \sim 15 - 50 \) days. Given the Fermi-GBM detection of a gamma-ray transient with fluence...
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F \sim 2.4 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ cm}^{-2} \text{ (Goldstein et al. 2017)}, \text{ which gives } E_{\text{jet}} \sim 5 \times 10^{48} \text{ erg for a fiducial } \gamma \text{-ray efficiency } \eta_{\gamma} = 0.1, \text{ we infer a mildly relativistic } \Gamma_{0} \sim 2 \text{ for } t_{pk} \sim 15 - 30 \text{ days}. \text{ After peak, when most of the fireball energy has been transferred to the ISM, the standard afterglow scalings apply. The latest CVO detection implies } E_{\text{iso,iso}} \sim 4 \times 10^{48} \text{ erg if } \nu_{r} < \nu_{\gamma}, \text{ or } E_{\text{iso,iso}} \sim 10^{49} \text{ erg if } \nu_{r} > \nu_{\gamma}. \text{ Radio observations acquired around the same time (Alexander et al. 2017a) constrain } p \sim 2.2. \text{ Mildly-relativistic outflows with similar } \Gamma_{0} \text{ and } E_{\text{iso}} \text{ that are found in shocks from supernovae (SN) with fast ejecta (i.e., relativistic SNe) are well described by } p \sim 3 \text{ (e.g., Chevalier \\& Fransson 2006; Soderberg et al. 2010; Chakraborti et al. 2015). From a purely theoretical perspective, both analytical models and PIC (particle-in-cell) simulations confirm that } p = 2.2 \text{ is expected in the cases of ultra-relativistic shocks where particle acceleration is very efficient. We thus conclude that a late onset of a weak on-axis afterglow emission is unlikely to provide a satisfactory explanation of our observations across the electromagnetic spectrum, and we consider alternative explanations below.}

3.2. Constraints on Off-axis Jets

A delayed onset of the X-ray emission can originate from the presence of an off-axis jet, originally pointed away from our line of sight. For a simple model of a point source at an angle \( \theta_{obs} \) moving at a Lorentz factor \( \Gamma \), the peak in the light curve occurs when the beaming cone widens enough to engulf the line of sight, \( \Gamma(t_{pk}) \sim 1/\theta_{obs} \) (e.g., Granot et al. 2002). This is a purely dynamical effect that does not depend on the microphysical parameters \( \epsilon_{e} \) and \( \epsilon_{B} \) (which instead concurs to determine the overall luminosity of the emission). From Granot \\& Sari (2002), the evolution of the Lorentz factor of a blast-wave propagating into an ISM medium can be parameterized as \( \Gamma(t) \sim 6.68(E_{\text{iso,iso}}/n_{0})^{-1/8}t_{\text{days}}^{3/8} \), which gives \( \theta_{obs} \sim 0.15(E_{\text{iso,iso}}/n_{0})^{-1/8}t_{\text{pk, days}}^{1/8} \) or \( \theta_{obs} \sim 0.2(E_{5.0}/n_{0})^{-1/6}t_{\text{pk, days}}^{1/6} \). Before peak the off-axis model predicts a steep rise, with the flux scaling \( \propto t^{2} \). As we argued above, the mild temporal evolution of the detected X-ray emission suggests a peak not too far from our last epoch of observation at \( \sim 15 \) days. We find \( \theta_{obs} \sim (15 - 30^{\circ})/(E_{5.0}/n_{3})^{-1/6} \) for \( t_{pk} = 15 - 70 \). If GW170817 harbored a relativistic off-axis jet with similar parameters to cosmological short GRBs (\( E_{5.0} \sim 10^{49-50} \text{ erg} \) and \( n \sim 10^{-3} \text{ cm}^{-3} \), Fong et al. 2015), this simple analytical scaling suggests off-axis angles \( \theta_{obs} \sim 20^{\circ} - 40^{\circ} \).

The actual values of the flux detected (and undetected) in the X-rays and radio pose additional constraints that break the model degeneracy in \( E_{5.0} \) and \( n \) as a function of \( \epsilon_{e} \) and \( \epsilon_{B} \). We employ realistic simulations of relativistic jets propagating into an ISM medium to fully capture the effects of lateral jet spreading with time, finite jet opening angle and transition into the non-relativistic regime. To this aim, we run the publicly available code BOXFIT (v2; van Eerten et al. 2010; van Eerten \\& MacFadyen 2012), varying \( E_{5.0}, n, p, \epsilon_{e} \) and \( \theta_{j} \) (jet opening angle), and calculate the off-axis afterglow emission observed as different lines of sight \( \theta_{obs} \), with \( \theta_{obs} \) varying from \( 5^{\circ} \) to \( 90^{\circ} \) (i.e. equatorial view). We explore a wide portion of parameter space corresponding to \( E_{5.0} = 10^{49} - 10^{50} \text{ erg} \), \( n = 10^{-4} - 1 \text{ cm}^{-3} \), \( \epsilon_{e} = 10^{-4} - 10^{-2} \). In our calculations we assume the fiducial value \( \epsilon_{e} = 0.1 \) (e.g., Sironi et al. 2015). For each parameter set, we consider two values for the power-law index of the electron distribution \( p = 2.4 \) (median value from short GRBs afterglows from Fong et al. 2015) and \( p = 2.2 \) (as expected from particle acceleration in the ultra-relativistic limit, Sironi et al. 2015), and we run each simulation for a collimated \( \theta_{j} = 5^{\circ} \) jet and a jet with \( \theta_{j} = 15^{\circ} \), representative of a less collimated outflow. As a comparison, the measured \( \theta_{j} \) in short GRBs range between \( 3^{\circ} \) and \( 10^{\circ} \) with notable lower limits \( \theta_{j} > 15^{\circ} \) and \( \theta_{j} > 25^{\circ} \) for GRBs 050709 and 050724A (Fong et al. 2013 and references there in).

The results from our simulations can be summarized as follows: (i) While we find a set of solutions with \( p = 2.4 \) that can adequately fit the X-ray light-curve, all of these simulations violate our radio limits as we detail in Alexander et al. (2017a). Models with \( p \geq 2.4 \) are ruled out and we will not discuss these simulations further. (ii) Models that intercept the measured X-ray flux, but with \( t_{pk} \gg 15 \) days, overpredict the radio emission, for which we have observations extending to \( t \sim 40 \) days (Alexander et al. 2017a). Jets with \( E_{5} > 10^{49} \text{ erg} \) belong to this category and are not favored. (iii) Most high-density environments with \( n \sim 0.1 - 1 \text{ cm}^{-3} \) cause an earlier deceleration of the jet. As a consequence, these models require \( \theta_{obs} \) between \( 40^{\circ} \) and \( 60^{\circ} \) to match the X-ray observations (i.e. a range of \( \theta_{obs} \) not favored by the early blue colors of the kilonova, Cowperthwaite et al. 2017; Nicholl et al. 2017 and are not consistent with the radio limits. (iv) Low-energy jets with \( E_{5} \sim 10^{48} \text{ erg} \) also have shorter deceleration times and require \( \theta_{obs} > 45^{\circ} \) to explain the X-ray observations (and are consequently not favored by the kilonova colors). (v) Finally, wider jets have a larger allowed parameter space and are favored based on their broader light-curves around peak time.

We identify a family of solutions that adequately reproduce the current data set across the spectrum (Figures 2-3). The successful models are characterized by an off-axis jet with \( 10^{49} \text{ erg} \leq E_{5} \leq 10^{50} \text{ erg} \), \( \theta_{j} = 15^{\circ} \) viewed \( \sim 20^{\circ} - 40^{\circ} \) off-axis and propagating into an ISM with \( n \sim 10^{-4} - 10^{-2} \text{ cm}^{-3} \), depending on the value of \( \epsilon_{e} = 10^{-4} - 10^{-2} \). The dependency of the best fitting \( \theta_{obs} \) values on \( n \) and \( \epsilon_{B} \) is illustrated in Fig. 4. The successful models are portrayed in Fig. 2.3. Collimated outflows with \( \theta_{j} = 5^{\circ} \) satisfy the observational constraints only for \( E_{5} = 10^{49} \text{ erg} \), \( \epsilon_{e} = 10^{-4} \), \( n \sim 10^{-3} \text{ cm}^{-3} \) and \( \theta_{obs} \sim 16^{\circ} \). From Fig. 2.3 it is clear that the optical emission from the off-axis afterglow (green line in the right-column plots) is always negligible compared to the contemporaneous kilonova emission. It is also worth noting that these models predict a radio flux density that is close to our flux limits (purple line and points), thus providing support to our tentative VLA detection at \( t \sim 20 \) days at the level of \( \sim 20 \mu Jy \) (Alexander et al. 2017a). Our favored models are not in disagreement with the radio detection of a faint transient at the level of \( S/N = 5 \) previously reported by Mooley et al. (2017) and Corsi et al. (2017) \( \sim 15 \) days post merger (Hallinan et al. 2017), and are fully consistent with our radio detection at 6 GHz at \( t = 39.4 \) days, as detailed in Alexander et al. (2017a).

3.3. Emission from the Central Engine

Short GRBs are sometimes accompanied by late time X-ray emission (e.g. Perley et al. 2009; Margutti et al. 2011; Fong et al. 2014), which may originate from long-lived central engine, such as an accreting black hole (e.g. Perna et al. 2006) or a millisecond magnetar (e.g. Metzger et al. 2008). GW170817 was accompanied by luminous optical and infrared emission, consistent with predictions for the kilonova emission originating from r-process radioactive heating of the
GW170817AX-rays

Fig. 2.— Off-axis jet model with \( \theta_j = 15^\circ \) and \( E_k = 10^{50} \) erg that best represents the current set of X-ray and radio observations (see Fig. 1 for models with \( E_k = 10^{50} \) erg). For this model, \( n = 10^{-4} \) cm\(^{-3} \), \( \epsilon_B = 10^{-4} \). Left panel: X-ray emission for observers at different \( \theta_{\rm obs} \) (colored lines). The black line identifies the best-fitting model, which has \( \theta_{\rm obs} \approx 22^\circ \). Grey triangles: Swift-XRT upper limits. Black symbols: CXO observations. We show the results from Troja et al. (2017) as an upper triangle (lower limit) for graphics purposes only. Central panel: radio (10 GHz, solid purple line) and optical emission (\( r \)-band, solid green line) for the best-fitting model compared to our VLA limits (purple triangles, Alexander et al. 2017) and emission from the kilonova (green dashed line, Cowperthwaite et al. 2017). The optical off-axis afterglow represents a negligible contribution to the kilonova emission at \( t < 30 \) days. Right column: SED of the best-fitting model at the time of the X-ray detection 15.4 days. The best-fitting off-axis models with \( E_k = 10^{49} \) erg are shown in Fig. 3.

4. SUMMARY AND CONCLUSIONS

We present the first X-ray detection from a GW source thanks to CXO observations. These observations enabled the first discovery of rising X-ray emission that we interpret in the context of isotropic or collimated outflows (on-axis and off-axis) with different properties. Our results can be summarized as follows:

- On-axis afterglow emission similar to that typically observed in cosmological short GRBs (i.e. \( E_{k,iso} \approx 10^{51} \) erg) is clearly ruled out.
- A late (on-axis or isotropic) afterglow onset, due to the deceleration of a mildly relativistic outflow can explain the X-ray observations but likely violates the radio limits.
- A central-engine origin of the X-ray emission is disfavored, as from the kilonova parameters that we infer in Cowperthwaite et al. (2017), Nicholl et al. (2017); Chornock et al. (2017) we derive a large optical depth that would prevent the X-rays from escaping and reach the observer.
- Current radio and X-ray observations are consistent with the emission from a relativistic jet with \( \theta_j = 15^\circ \), \( 10^{49} \) erg \( \leq E_k \leq 10^{50} \) erg, viewed \( \sim 20^\circ - 40^\circ \) off-axis and propagating into an ISM environment with \( n = 10^{-4} - 10^{-5} \) cm\(^{-3} \), depending on \( \epsilon_B = 10^{-4} - 10^{-2} \). Very collimated outflows with \( \theta_j \sim 5^\circ \) are not favored by observations.

The discovery of X-ray emission from GW170817 marks a milestone in connecting on-axis GRBs with BNS mergers, and sets the stage for all future GW events with detected X-ray emission. Late-time X-ray monitoring of GW170817 at \( t \geq 100 \) days (when it will be observable again with the CXO) will provide additional, crucial information to solve the model degeneracies and test our predictions. Our inferences on the observing angle with respect to the jet axis might be testable using gravitational wave information from Advanced LIGO/Virgo on the binary inclination, inasmuch as the accuracy of the GW measurement is comparable to ours.
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Fig. 4.— Left y-axis and black thick line: cumulative GW detection probability at observing angles $< \theta_{\text{obs}}$ with respect to the binary axis, calculated following Metzger & Berger (2012) and Schutz (2011). Orange points: $\theta_{\text{obs}}$ as inferred from our simulations of off-axis jets with $E_k = 10^{49}$ erg (filled circles) or $E_k = 10^{49}$ erg (filled square) and $\theta_j = 15^\circ$ that satisfy all the observational constraints from X-ray and radio observations currently available, as a function of the ISM density $n$ (right y-axis). A kilonova with blue colors is expected for $\theta_{\text{obs}} \leq 45^\circ$ (Sekiguchi et al. 2016), shaded blue area. The value of $\epsilon_B$ for each successful simulation is also reported in the plot.

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