Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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The neutron star neutron star merger GW170817: a multi–messenger study

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Abstract. We join gravitational-wave and electromagnetic data to implement a combined simultaneous fit of the GW170817 event. The LIGO-Virgo analysis includes the estimation of the inclination, the angle of the binary with respect to the gravitationa-wave detector network line of sight. From the observations of the afterglow, instead, we can recover the viewing angle. The inclination and the viewing angle are supplementary angles, and can be treated as a single parameter. The value of the inclination that we recover from the fit is in agreement with the LIGO-Virgo previous works, with an uncertainty that is 10-fold smaller, thanks to contribution of the electromagnetic data. Moreover, with the inclusion of the gravitational-wave data, the degeneracy between the viewing angle and the jet opening angle is broken. This procedure is useful not only for analyzing GW170817, but any gravitational-wave event with an electromagnetic counterpart.

Keywords. gravitational waves, gamma rays: bursts, methods: data analysis, stars: neutron.

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1. Introduction

On August 17, 2017, two Advanced LIGO detectors and Advanced Virgo observed the neutron star binary inspiral event GW170817 with a total mass less than any previously observed binary coalescence [LIGO, Virgo Collab (2017a)].

The collisions of two neutron stars form highly relativistic and collimated outflows (jets) that power gamma-ray bursts (GRBs) of short (less than two seconds) duration [Eichler *et al.* (1989)]. Therefore, gravitational-wave (GW) events from such mergers should be associated with GRBs, but the majority of these bursts should be seen off-axis, that is, they should point away from Earth [Rhoads *et al.* (1997)].

The short, hard burst GRB 170817A [Goldstein et al. (2017); Sachenko et al. (2017)] followed the GW detection after about 2 sec, confirming the compact binary progenitor model [LIGO, Virgo Collab (2017b)]. This is a ground breaking event, as it paved the way for multi-messenger astrophysics. Observations in the X-ray [Troja *et al.* (2017)] and radio [Troja *et al.* (2018); Hallinan *et al.* (2017)] frequencies followed, they are consistent with a short GRB viewed off-axis [Van Eerten *et al.* (2010)]. The source, in the optical, infrared and ultraviolet, called AT 2017gfo [Coulter *et al.* (2017)], is in the galaxy NGC 4993, at almost 40 Mpc distance [LIGO, Virgo Collab (2017b)].

Since the GW and the jet model used to fit the two datasets share the viewing angle (or the inclination) of the system, the main goal of this work is to develop a joint fit of GW and electromagnetic (EM) datasets, in order to get more precise information about that common parameter, in view of the upcoming fourth GW observing run (O4). The analysis is carried out on GW170817 data for demonstrative purposes.

2. Methods

The low luminosity of the GW170817 gamma-ray emission and the atypical behaviour of the afterglow point to a highly relativistic structured jet seen at an angle of 20-30 deg from its axis. The opening angle of the jet θ_c and the viewing angle θ_v of the system are correlated. This degeneracy is in part broken thanks to the declining phase of the afterglow, but it is still present. An independent dataset which gives information about the viewing angle can be added to the fit and break the degeneracy. In the case of GW170817, this dataset could be the high resolution imaging of the radio source associated with GW170817 [Mooley *et al.* (2018)]. This is not always the case, so another independent dataset is the GW detector network timeseries.

We use Bayesian methods to process the data, in particular, the Bilby library [Smith *et al.* (2020)] to handle the GW data and dynesty [Speagle *et al.* (2020)] as sampling package. The parameters $\vec{\theta}$ can be divided in three sets: the EM parameters; the GW parameters; the parameters shared by the EM and GW models. Assuming that the datasets are independent, the joint likelihood of the gravitational, d_{GW}, and electromagnetic, d_{EM}, datasets is given by the product of the two likelihoods

$$\mathcal{L}_{GW+EM}(d_{GW}, d_{EM}|\vec{\theta}) = \mathcal{L}_{GW}(d_{GW}|\vec{\theta}) \times \mathcal{L}_{EM}(d_{EM}|\vec{\theta}). \tag{2.1}$$

The EM and GW likelihoods are both Normal distributions. Finally, the posterior probability distribution for $\vec{\theta}$ is defined according to the Bayes theorem

$$p(\vec{\theta}|d_{GW}, d_{EM}) \equiv \frac{\mathcal{L}_{GW+EM}(d_{GW}, d_{EM}|\vec{\theta})\pi(\vec{\theta})}{\mathcal{Z}_{\vec{\theta}}} \tag{2.2}$$

where $\pi(\vec{\theta})$ is the prior (multidimensional) probability distribution for the parameters and $\mathcal{Z}_{\vec{\theta}}$ is the Bayesian evidence, obtained by marginalizing the joint likelihood over the GRB and GW parameters. The total number of parameters is 21.

The light curve of GRB 170817A is modelled using the afterglowpy software [Ryan *et al.* (2020)] and shown in Fig. 1. The radio dataset is taken from [Makhathini *et al.* (2021)], while the optical and infrared from [Troja *et al.* (2021)]. The software allows to fit the jet with a Gaussian distribution of lateral energy. For the Gaussian structured jet, we assume energy drops according to $E(\theta) = E_0 \exp(-\theta^2/2\theta_c^2)$, up to a truncating angle θ_w. The parameters are 8: the viewing angle θ_v, between the jet axis and the line of sight; the jet opening angle θ_c; the isotropic equivalent energy E_0; the circumburst medium number density n_0; the jet total width θ_w; we assume that the electrons are shock-accelerated and their energy distribution is a power law with slope -p; the fraction of post-shock internal energy in the electrons ϵ_e; the fraction of post-shock internal energy in the magnetic field ϵ_B. The last 3 parameters deal with the synchrotron emission. The priors of these parameters are reported in [Troja *et al.* (2018)].

According to general relativity, GWs emitted by the inspiral of two compact objects in a quasicircular orbit are characterized by a chirplike time evolution, namely the more the orbit shrinks, the larger the amplitude and the frequency of the wave are.

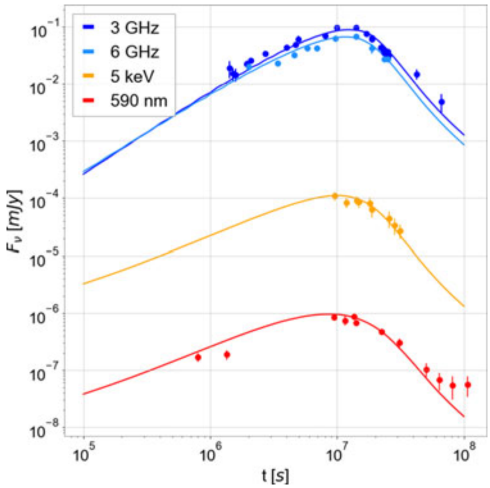

Figure 1. Light curve of GW170817 and afterglow model. The different shades of blue represent observations at 3 GHz (blue) and 6 GHz (light blue). The optical and X-ray (5 keV) bands are in orange and red respectively.

IMRPhenomPv2_NRTidal [Dietrich *et al.* (2017)] is the GW signal we choose to process GW170817. It includes intrinsic parameters that describe the components of the binary and extrinsic parameters that, among other things, determine the location and orientation of the binary with respect to the observer. The intrinsic parameters include the chirp mass [Finn *et al.* (1993)] and the mass ratio. The spin angular momenta $\vec{S}_i$ of the two binary components represent six additional intrinsic parameters. The amount of deformation due to matter effects is described by a mass-weighted linear combination of the tidal parameters of the two neutron stars, $\tilde{\Lambda}$ [Wade *et al.* (2014)]. The remaining signal parameters are extrinsic, they give the localization and orientation of the binary. The position in the sky (right ascension and declination) is fixed, according to the known position of AT 2017gfo [LIGO, Virgo Collab (2017d)]. The luminosity distance is fixed at 40 Mpc. The inclination of the system is defined as θ_{JN}, the angle between the total angular momentum **J** and the line of sight **N**, namely $\cos\theta_{JN} = \hat{J} \cdot \hat{N}$. The GW priors are set as in [Romero-Shaw *et al.* (2020)].

The common parameter between EM and GW models is the inclination θ_{JN}. It actually is a GW parameter, but it is easily linked with the viewing angle θ_v. In GW170817 the two neutron stars are rotating clockwise, so the two angles are supplementary. The prior for θ_{JN} is sinusoidal, the bounds are such that the viewing angle goes from 0 to 35 deg, they were chosen to match the EM prior but also to speed up the fit.

3. Results and discussion

The fitted model of the light curve is under-predicting the late time observations, see Fig. 1 ([Troja *et al.* (2020)] for a deeper discussion), the parameters are in agreement within 3 σ with the results in [Troja *et al.* (2021), Troja *et al.* (2020)]. We find $\log(E_0) = 50.7 \pm 0.1$, $\theta_c = 0.10 \pm 0.01$ rad, $\theta_w = 0.97^{+0.48}_{-0.53}$ rad, $\log(n_0) = -3.6^{+0.1}_{-0.3}$, $p = 2.14 \pm 0.02$, $\epsilon_e = -0.10^{+0.05}_{-0.06}$ and $\epsilon_B = -1.6 \pm 0.2$ (medians, 5th and 95th percentiles).

The GW parameters from the joint fit are in agreement with the ones presented in [LIGO, Virgo Colla (2019); Romero-Shaw *et al.* (2020)], for example the chirp mass is $\mathcal{M} = 1.1975 \pm 0.0001$, the tidal deformability $\tilde{\Lambda} = 469^{+471}_{-292}$ and the mass ratio $q = 0.85 \pm 0.13$ (medians, 5th and 95th percentiles).

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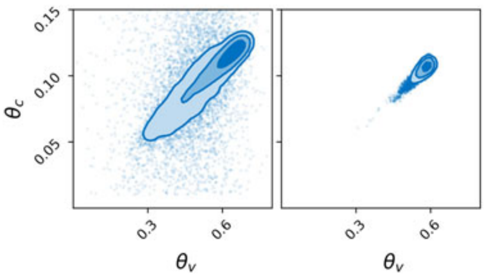

Figure 2. 2D distribution of the viewing angle and jet opening angle. The left and right hand sides report the result from the afterglow-only and the EM+GW fit, respectively. The contours represent the 1σ, 1.5σ and 2σ levels.

The common parameter, θ_{JN}, is 147 ± 2 deg, which is in agreement within 1σ with the one found in the GW analysis [LIGO, Virgo Colla (2019)], moreover the error is more than 10 times smaller in this work, thanks to the inclusion of the EM information. The corresponding viewing angle is $\theta_v = 33 \pm 3$ deg, which also is in agreement within 1σ with the results from [Troja *et al.* (2021)].

Fig. 2 shows a comparison of the 2D distributions of the viewing angle and jet opening angle in the case of EM only fit (on the left, done on the same EM dataset of the joint fit) and EM and GW fit (on the right). The plots are in the same scale. The degeneracy is broken, as expected.

In this work, we show that multi-messenger astrophysics provides untapped and complementary types of information, that we exploit to break the degeneracy between the viewing angle and the jet opening angle. Additionally, the uncertainty on the inclination is more than 10 times smaller with respect to a GW-only analysis, thanks to the EM contribution. This brings more precise information about the geometry of the system. Clearly, the geometry can be linked to the physics of the r-processes in the kilonova and to relativistic jet theory. The analysis developed in this work can be easily generalized to other future events of gravitational-waves with EM counterparts.

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