GW170817: implications for the local kilonova rate and for surveys from ground-based facilities

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ABSTRACT

We compute the local rate of events similar to GRB 170817A, which has been recently found to be associated with a kilonova (KN) outburst. Our analysis finds an observed rate of such events of $R_{\mathrm{KN}} \sim 352^{+810}_{-281} \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$. After comparing at their face values this density of sGRB outbursts with the much higher density of Binary Neutron Star (BNS) mergers of $1540^{+3200}_{-1220} \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, estimated by LIGO-Virgo collaboration, one can conclude, admittedly with large uncertainty that either only a minor fraction of BNS mergers produces sGRB/KN events or the sGRBs associated with BNS mergers are beamed and observable under viewing angles as large as $\theta < \sim 40^\circ$. Finally we provide preliminary estimates of the number of sGRB/KN events detected by future surveys carried out with present/future ground-based/space facilities, such as LSST, VST, ZTF, SKA and THESEUS.

Key words: gravitational waves – stars: gamma-ray burst: general – stars: supernovae: general

1 INTRODUCTION

In the last decades BNS systems have been targets of interest because of their direct link with some of the most relevant topics of modern astrophysics, such as the indirect confirmation of the existence of GWs through radio observations (Hulse et al. 1975), the predicted connection with short Gamma-Ray Bursts (sGRBs) (Eichler et al. 1989) and their direct observations from X and γ satellites e.g. (Gehrels et al. 2005) and their detection as sources of GWs (Abbott et al. 2017a,b). During a BNS merger some sub-relativistic ejecta mass $\sim 10^{-3} - 10^{-2} \, M_\odot$ is thrown out along the orbital plane at a modest fraction of the speed of light, $\beta = v/c = 0.1 - 0.3$ and rapid neutron capture in the sub-relativistic ejecta e.g. (Lattimer & Schramm 1976; Metzger et al. 2010; Tanaka & Hotokezaka 2013) is hypothesized to produce a KN, an optical and near-infrared signal lasting hours to weeks (Li & Paczynski 1998; Tanvir et al. 2013; Smartt et al. 2017; Pian et al. 2017) powered by radioactive decay. Finally, this sub-relativistic ejecta transfer most of their kinetic energy ($\sim 10^{50} - 10^{51} \, \text{erg}$) to the shocked ambient medium.

The rate of BNS mergers can be constrained in several ways: by modeling the evolution of binary systems through populations synthesis simulations e.g. (Sadowski et al. 2008; Benacquista & Downing 2013; Ziosi et al. 2014; Dominik et al. 2015; Belczynski et al. 2016; Chruslinska et al. 2018), by the direct measurements of coalescence rates of BNS in the Milky Way from pulsar observations (Narayan et al. 1991; Kalogera et al. 2004), from the cosmic abundance of r-process elements such as Europio (Matteucci et al. 2014; Vangioni et al. 2016) and from gravitational wave observa-

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for a galaxy number density of $10^3$ per Gpc$^{-3}$ yr$^{-1}$ (Kalogera et al. 2004). In spite of many efforts the rate of sGRBs is still uncertain within a factor of a few (Belczynski et al. 2008; Petroff et al. 2013). Nevertheless, the measurement of the BNS merging rate can be inferred by measuring the frequency of occurrence of sGRBs, which are believed to occur during the coalescence of two NSs (Eichler et al. 1989; Berger 2014; Avanzo 2015). In this paper, we show that the discovery of the electromagnetic counterpart of GW 170817 (Abbott et al. 2017b and reference therein) can help to significantly constrain this broad range of uncertainty. On the basis of this new rate we provide preliminary estimates of the number of KNe detected in surveys carried out by present and next generation ground based facilities/space missions, such as LSST, VST, ZTF, SKA and Theseus.

2 THE RATE OF BNS MERGING

The rate of expected merging events has been estimated based on the observed galactic population of double NS binaries containing a radio pulsar (Phinney et al. 1991; Narayan et al. 1991; Kalogera et al. 2001; Burgay et al. 2003). A reference number for the BNS merging rate in the Galaxy is $\sim 80^{+200}_{-60}$ Myr$^{-1}$, that can be converted to $800^{+2000}_{-600}$ Gpc$^{-3}$ yr$^{-1}$ for a galaxy number density of $10^{-5}$ Mpc$^{-3}$ (Kalogera et al. 2004). This rate has been recently revised by Chruslinska et al. (2018) (see Table 1). Population synthesis studies of binary systems give results consistent with the above rates (Perna & Belczynski 1991; Belczynski et al. 2002, 2007). Taking into account the BNS merging rate measured from the detection of GW 170817 (Abbott et al. 2017a) and the design sensitivity of Advanced LIGO and Virgo, gravitational signals from BNS mergers are expected to be detected at a rate of one every 4-90 days (Abbott et al. 2018).

3 THE RATE OF SGRBS

In this section we review the estimates of the local rate of sGRBs. In spite of many efforts the rate of sGRBs is still uncertain within a factor $\sim 10^3$, as it appears from an inspection of Tab. 2. There are many parameters that affect the estimate of the rate of sGRBs, such as: i) the shape of the luminosity function assumed for the sGRBs; ii) the minimum of the luminosity function; iii) the redshift distribution assumed for the sGRBs; iv) the time delay distribution of the merging time (from the formation of the NS to their merging); v) the beaming factor. Among these the minimum of the sGRB Luminosity function $L_{\text{min}}$, is the parameter that mostly affects the local rate, as it can be clearly seen in the equation below that has been derived by Guetta & Stella (2009)

$$R_{sGRB} \sim \left( \frac{R_0}{\text{Gpc}^{-3} \text{yr}^{-1}} \right) \left( \frac{L_{\text{min}}}{10^{59}} \right)^{-0.5}$$

(1)

Where $R_0$ is the central value given in Table 2. In Equation 1, it is assumed that the luminosity function of sGRBs can be parametrized by a broken power law. The power law index for the low luminous part that best reproduced the data is $\alpha \sim 0.5$ (Guetta & Piran 2005). Several authors have tried to estimate the local rate of sGRBs by using the observed peak flux distribution and redshift distribution of the sGRBs, but still the uncertainties are large.

3.1 Rates smaller than 1 Gpc$^{-3}$ yr$^{-1}$

In this subsection we describe briefly the method used by different authors to derive the local rate of sGRBs. Guetta & Piran (2005) fitted the properties of a simulated sGRB population, described by the parametric luminosity and redshift distribution, to a set of observational constraints derived from the population of sGRBs detected by BATSE. On the other hand BATSE was insensitive to low luminous GRBs and in view of Eq. 1, this means to increase the value of $L_{\text{min}}$ and to decrease the local sGRB rate. Ghirlanda et al. 2016 find a similar result after selecting a "bona fide" sample of 211 Fermi/GBM bursts with a peak flux larger than 5 ph cm$^{-2}$ s$^{-1}$ aimed at avoiding the incompleteness effects affecting observations close to the detection threshold. By performing this selection Ghirlanda et al. 2016 consider only the bright sGRBs ( $\gtrsim 10^{50}$ erg) which corresponds to increase $L_{\text{min}}$ in Eq. 1 and therefore to decrease the local sGRB rate. Both Guetta & Piran 2005 and Ghirlanda et al. 2016 assume that sGRBs follow the star formation rate (SFR).

$$f_{b}^{-1} = 1 - \cos \theta$$

where $\theta$ is the jet half-opening angle
Local sGRBs rate $R_0$ (Gpc$^{-3}$ yr$^{-1}$) instead of a broken power law: the local rate of sGRBs (Nakar et al. 2006). The latter au-

The form of the luminosity function also affects the minimum luminosity function assumed, as it is apparent

These values can be increased if we decrease sGRB redshift and delay-time distributions considered in Table 2 for Guetta & Piran 2006 correspond to differ-

The “observed” local rate of sGRBs as a function of

3.2 Rates larger than 1 Gpc$^{-3}$ yr$^{-1}$

Several authors find a larger local rate for the sGRBs per-

Taking into account selection effects that modify the Swift de-

4 UPPER LIMITS TO THE KN RATE FROM OBSERVATIONS

In the last decade several sky surveys have been designed for the detection of different classes of transients such as Supernovae, Asteroids, Novae etc. Some of them as ATLAS (Tonry 2011), DES (Doctor et al. 2017) and DLT40 (Yang et

5 THE RATE OF GRB 170817A-LIKE EVENTS

GRB 170817A and GW170817 events were detected by Fermi-GBM (Fermi-GBM 2017) and INTEGRAL, and by Advanced LIGO and Advanced Virgo experiment. The two events, the binary coalescence and the sGRB, were detected ~ 1.7s apart (Abbott et al. 2017a; Savchenko, et al. 2017). About 11h later the optical counterpart was discovered by (Coulter et al. 2017) in the outskirt of the early type galaxy NGC 4993, located at ~ 41 Mpc (Cantiello et al. 2018).

Within one hour and before the announcement of discovery, five other team reported independent detection of the optical transients (Arcavi, et al. 2017; Cowperthwaite, et al. 2017; Lipunov, et al. 2017; Tanvir, et al. 2017; Valenti et al. 2017).

In the following we will use the detection of a sGRB/KN event within 41 Mpc to constrain the rate of such sources. The GRB light curve shows a weak short pulse with a duration $T_{90}$ of about 2 s (50-300 keV). The time-averaged spectrum is well fit by a power law function with an exponential high-energy cutoff. The power law index is $\alpha = -0.89 \pm 0.5$. The 1.024-sec peak photon flux in the 50-300 keV band is $F \sim 0.74ph/s/cm^2$. This flux can be compared with the GBM

\begin{equation}
R_{\text{sGRB}} \sim \left( \frac{R_0}{4.1 \pm 0.5 \text{Gpc}^{-3} \text{yr}^{-1}} \right) f_\nu^{-1} \left( \frac{L_{\text{min}}}{5 \times 10^{49}} \right)^{-0.95}
\end{equation}

Guetta & Stella (2009) consider the possibility that a fraction of sGRBs come from the merging of dynamically formed binaries in globular clusters and infer the correspond-

This flux can be compared with the GBM
peak flux threshold of $F_{\gamma} \sim 0.50\, \text{ph/s/cm}^2$, then deriving the maximum distance ($D_{\text{max}} = 49\, \text{Mpc}$) to which the event could be detected, corresponding to the maximum volume ($V_{\text{max}} = 4.9 \times 10^{-4}\, \text{Gpc}^{-3}$). After considering the Fermi-GBM (similiar to the INTEGRAL/SPI-ACS) a low-orbit all-sky monitor (e.g. Meegan et al. 2009), with a sky coverage of $S_{\text{cov}} \sim 0.64$ and the number of years of operation ($T \sim 9\, \text{yr}$) of the GBM detector, the rate of sGRBs similar to the 170817A is:

$$R_{\text{sGRB}} = \frac{1}{V_{\text{max}}} \frac{1}{S_{\text{cov}}} \frac{1}{T} \sim 352\, \text{Gpc}^{-3}\, \text{yr}^{-1}.$$ (4)

The range of uncertainty on this rate is obviously large, however, in view of the figures reported in Tab. 2 and 3, it still provides interesting clues. On the basis of poissonian statistics applied to one positive detection (Gehrels 1986) we obtain a rate of $352+810 \times 2^{-281}$ Gpc$^{-3}$ yr$^{-1}$ that represents a substantial lower rate than the upper limits derived from the surveys reported in Tab. 3.

6 DISCUSSION

To convert the “observed” rate into the “true” rate of events, one has to correct the observed number for the beaming factor $f_B$. Unfortunately the value of $f_B$ is not well known, ranging from values as high as $f_B \sim 700-180$ corresponding to angles as small as $\theta = 3^\circ - 6^\circ$ (Ghirlanda et al. 2016), to intermediate values of $f_B \sim 30 - 40$ corresponding to moderately wide angles of $\theta \sim 15^\circ$ (Petrillo et al. 2013; Fong et al. 2015) up to small beaming factors $f_B \sim 10$ for angle as broad as $\theta \sim 30^\circ$ (Rezzolla et al. 2011; Granot et al. 2017).

By comparing their face values the density of BNS mergers and GRB 170817A-like events, i.e. $1540^{-3200}_{+1220}\, \text{Gpc}^{-3}\, \text{yr}^{-1}$ we find a range of values for the angles from which a GRB is observable of $\sim 10^\circ - 40^\circ$ in good agreement with most theoretical predictions (e.g. Lazzati et al. 2017). However the geometry of the outflow of GRB 170817A is still matter of discussion. The radio and X-rays that followed GW170817 are unlike any afterglow observed before, showing a gradual rise over ~100 days. They resemble the radio flare predicted long ago to follow BNS mergers. This emission arises from the interaction of the merger outflow with the external medium (Nakar & Piran 2011). Recently, Nakar & Piran (2018) have considered this model to explain the X-ray observations of GW170817 and they also infer that we have observed an off-axis emission of a “structured” jet, a conclusion which might appear in mild disagreement from that derived by (Troja et al. 2017), who support the idea of an off-axis view for GRB 170817A. Very recently Mooley et al. 2018 have found that the late-time emission of GRB 170817A is dominated by a narrowly collimated jet, characterized by an opening angle of $\theta \sim 5^\circ$ and they conclude that the emission from the jet was likely observed from a viewing angle of $\sim 20^\circ$ degrees.

If we assume the distance of $\sim 200\, \text{Mpc}$ as a plausible threshold for future detection of GWs associated with BNS mergers in the advanced LIGO/Virgo experiments (Abbott et al. 2018), we expect to detect within the corresponding volume of $3.4\times 10^{-2}\, \text{Gpc}^{-3}$, about $N_{\text{KNe}} = f_b^{-1} \times 12^{27}_{10}$ KNe yr$^{-1}$.

7 KILONOVAE IN FUTURE LSST, VST, ZTF, SKA AND THESEUS SURVEYS

The relatively high rate of sGRB “170817A-like” that we have measured with this paper, from dozens to hundreds of events per Gpc$^{3}$ per year, suggests that future optical sky surveys, designed with an appropriate observational strategy, will be able to detect a significant number of KNe without GRB or GW triggers. In the following we will provide some preliminary estimates for the KNe detections from LSST, VST, ZTF, SKA and THESEUS surveys.

7.1 LSST

We assume a magnitude limit of R$\sim 24$ for a typical $2 \times 15$ square metres in visit and $\sim 20,000$ square degs patrolled in one year (LSST White Paper https://www.lsst.org/scientists/scibook) and $M_R \sim -16$ (Valenti et al. 2017) for the absolute magnitude at maximum of the KN associated with GRB 170817A. From this data we derive a sampled volume of $\sim 2.1\, \text{Gpc}^{3}\, \text{yr}^{-1}$ and therefore a number of KN detections of $\eta \sim 150 - 2440$ being $\eta$ the factor that accounts for the "efficiency" of the survey, which depends on several parameters, such as control time (i.e. a quantity that depends on the survey cadence and the photometric time scale evolution of the transient, see Cappellaro et al. 2015), sky conditions, technical downtime, scheduling constraints. After an assumption of $\eta \sim 50\%$ we find that the optical monitoring of the sky with LSST can discover $\sim 75 - 1220$ KN events (GW170817-like) per year within $z \sim 0.25$.

7.2 VST

After assuming a limiting magnitude of R$\sim 22.5$ in $t_{\text{exp}} \sim 1\, \text{min}$ (Brocato 2017; Grado et al. 2018) and $M_R \sim -16$ (Valenti et al. 2017) for the absolute magnitude at maximum of a 170817-like KN, and a patrolled field of 10,000 square degrees we find a sampled volume of 0.13 Gpc$^{-3}$, which implies, for $\eta = 0.50$, a number of "observable" KNe of $\sim 5 - 76$ KNe/yr. However, an observational strategy based on a survey devoted to the continuous patrolling of known galaxy clusters within hundreds of Mpc would increase the number of KN detections. For example, with a field of view of $\sim 1$ square degree, VST can monitor a large sample of galaxies ($\geq 70$) of the Hydra cluster with only 4 pointings. Considering a slightly different point of view, VST is expected to play a key role during the next O3 observing run of LIGO/Virgo collaboration (LVC). In fact, the O3 network of three interferometers is expected to reduce the uncertainties of the localization of GW events to few tens of square degrees with respect with previous runs. This allows VST to cover $\geq 90\%$ of the LVC sky map probability largely increasing the efficiency in discovering KNe.
candidates and in providing observational constraint on the rate of nearby (≤ 200 Mpc) KN events.

7.3 ZTF

The Zwicky Transient Facility (ZTF) is a new-generation time-domain survey currently operating at the Palomar Observatory. We assume a magnitude limit of R ~ 20.5 for a typical exposure of 30s (Bellm & Kulkarni 2017) and ~ 20,000 square degrees of sky continuously patrolled and M_R ~ -16 for the absolute magnitude at maximum of a KN (Valenti et al. 2017). We derive a patrolled volume of ~ 1.6 x 10^{-2} Gpc^3, and therefore a number of kilonova detections of \( N_{K\nu} = \eta \times 5.6^{+10}_{-4.5} \) KNe yr^{-1}.

7.4 SKA

The Square Kilometre Array (SKA) will survey large areas of the sky with close to \( \mu \)Jy sensitivities, which in principle would allow also to detect KNe from the already programmed SKA surveys. For the sake of simplicity, we discuss here three continuum generic surveys planned with the SKA1 (see Table 4). For each survey, we assume that the sampled area and the rms are obtained after one year of observations, and 3x10 min visits of the same field to reach the quoted sensitivity. We assume that the peak of brightness of GW170817 at 2.5 GHz was \( S_{\nu} \approx 100 \mu\text{Jy} \) e.g. (Margutti et al. 2018), corresponding to a monochromatic radio luminosity of \( L_{\nu} \approx 2.0 \times 10^{26} \text{erg/s/Hz} \) at the distance of its host galaxy. GW170817 peaked in the radio (at ~ 2.5 GHz) around day 163. Given the relatively standard radio synchrotron behaviour of the KN in GW170817, the peak at the nominal frequency of SKA of 1.7 GHz is expected to occur around day ~163 x (2.5/1.7) \( \approx 240 \) d. Therefore, three visits over a year are enough to reliably detect any KN in the radio. Hence, the factor \( \eta \) that accounts for the efficiency of the survey can be safely assumed to be very close to one. However, the sensitivity of the radio surveys forces us to restrict the search for KNe only inside the "local" universe. After assuming a 5-\( \sigma \) threshold for a bona fide detection in a blind survey, the maximum distance to which we can confidently detect new objects is of \( \sim 82, 193, \) and 373 Mpc for SKA1-Mid-A, SKA1-Mid-B, and SKA1-Mid-C, respectively. The volumes sampled by the planned SKA1 surveys after one year are just a tiny fraction of a Gpc^3 (see Section 5) the expected rate of kilonovae to be detected by blind radio surveys such as the ones described above is therefore quite meager. The values reported in col. 5 of Tab. 4 are in fact very similar, since the number of detected KNe scales as follows (Pérez-Torres et al. 2015): \( N_{\text{det}} \propto \Delta_{\text{det}}^{3/2} / \Omega \), where \( \sigma_{\nu} \) is the sensitivity of the survey and \( \Omega \) the angular area covered. Plugging in the numbers for each of those surveys, we see that only the SKA1-Mid-A offers some chances of getting at most one (blind) detection of a KN after one year of observations. SKA1-Mid-B and SKA1-Mid-C, despite being significantly more sensitive than SKA1-Mid-A, cannot compensate the small area covered by those surveys.

2 http://www.ztf.caltech.edu/page/technical

8 CONCLUSIONS

The discovery of the KN associated with GRB 170817A/GW170817 has provided the community with a number of "foods for thought" and some of them have been examined in this paper.

i) we find an "observed" rate of sGRBs associated with KNe of \( 352^{+810}_{-281} \) Gpc^{-3} yr^{-1}, which is definitely larger, by 1-2 orders of magnitude, than most of the estimates reported in Tab. 2 (all rates have been normalized to \( f_{\text{p}} = 1 \)). This rate is in relatively good agreement with the value of \( 190^{+440}_{-160} \) Gpc^{-3} yr^{-1} found by (Zhang et al. 2018). The difference between the two estimates is mainly due do different Dmax adopted in the papers: 49Mpc vs. 65Mpc (Zhang et al. 2018). From a theoretical point of view these high rates can be reproduced for an appropriate choice of the minimum luminosity of the luminosity function, i.e. \( \sim 10^{47} \) erg rather than \( 10^{50-51} \) erg (see eq. 1 and fig. 1). As an alternative one should consider the possibility that GRB 170817A might be

\[ \text{GW170817 and the local kilonova rate} \ 5 \]

\[ \text{MNRAS 000, 1–77 (2018)} \]
the prototype of a class of peculiar/subluminous sGRBs, associated with KNe, which not necessarily form the main bulk of the sGRBs population. For example the subluminous SN 1987A that was discovered in the "local" universe belongs to a relatively tiny class, $\lesssim 10\%$ (Pastorello et al. 2004) of intrinsically rare subluminous type II SNe.

ii) The comparison between the value of "observed" KN rate presented in this paper with the much higher density of BNS mergers estimated by the LIGO/Virgo collaboration (Abbott et al. 2017a) points out that either a minor fraction of BNS mergers produce sGRBs characterized by an isotropic emission or most BNS mergers produce beamed sGRBs that can be observed under viewing angles as large as $\theta \sim 40^\circ$. This second scenario is supported by Mooley et al. 2018 who find for GRB 170817A a $\theta \sim 5^\circ$ collimated jet that was likely observed from a viewing angle of $\sim 20^\circ$ degrees.

iii) An "observed" rate of $\sim 352$ events per Gpc$^{-3}$ yr$^{-1}$ offers excellent perspectives for the identification of the electromagnetic counterpart of BNS events detected during next LIGO/Virgo observing runs. On the basis of our analysis we estimate that future optical surveys will be able to detect, within 200 Mpc, $N_{\text{det}} = f_{KNe}^{-1} \times 12^{+27}_{-10}$ KNe yr$^{-1}$.

iv) The relatively high frequency of occurrence of KNe will allow to some of the future facilities the direct detection of KNe without GW triggers. Particularly LSST will have the capability to discover dozens to hundreds of KNe up to $z \sim 0.25$, that is well beyond the current advanced LIGO/Virgo capabilities. An opposite trend is shown by SKA. Preliminary estimates indicate that this array of radio telescopes will have the capability to carry out wonderful follow-ups for KNe discovered by other facilities, while it will be not so efficient in discovering KNe during "blind" and "shallow" radio surveys.

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| SKA survey     | Area (sq. deg) | rms (µJy/beam) | Sampled Volume (Gpc$^3$ yr$^{-1}$) | $N_{\text{det}}$ (Gpc$^{-3}$ yr$^{-1}$) |
|---------------|----------------|----------------|-----------------------------------|--------------------------------------|
| SKA1-Mid-A    | 31,000         | 5.0            | $17 \times 10^{-4}$               | 0.61$^{+0.39}_{-0.36}$               |
| SKA1-Mid-B    | 500            | 0.9            | $3.6 \times 10^{-4}$              | 0.13$^{+0.09}_{-0.08}$               |
| SKA1-Mid-C    | 20             | 0.24           | $1.1 \times 10^{-4}$              | 0.04$^{+0.08}_{-0.02}$               |

**Table 4. Expected blind detections of KNe from planned SKA Generic Continuum Extragalactic Surveys**
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