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Low-Γ jets from Compact Binary Mergers as Candidate Electromagnetic Counterparts to Gravitational Wave Sources

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Abstract. Compact binary mergers, with neutron stars or neutron star and black-hole components, are thought to produce various electromagnetic counterparts: short gamma-ray bursts (GRBs) from ultra-relativistic jets followed by broadband afterglow; semi-isotropic kilonova from radioactive decay of r-process elements; and late time radio flares; etc. If the jets from such mergers follow a similar power-law distribution of Lorentz factors as other astrophysical jets then the population of merger jets will be dominated by low-Γ values. The prompt gamma-rays associated with short GRBs would be suppressed for a low-Γ jet and the jet energy will be released as X-ray/optical/radio transients when a shock forms in the ambient medium. Using Monte Carlo simulations, we study the properties of such transients as candidate electromagnetic counterparts to gravitational wave sources detectable by LIGO/Virgo. Approximately 78% of merger-jets result in failed GRB with optical peaks 14-22 magnitude and an all-sky rate of 2-3 per year.

Keywords. gamma rays: bursts, jets and outflows, gravitational waves.

1. Introduction

The merger of a binary system due to gravitational wave (GW) emission where the binary components are either neutron stars (NS) or stellar mass black holes (BH) is a potential source of GWs detectable by current gravitational wave detectors (e.g. LIGO/Virgo). In 2015, advanced LIGO made two unambiguous detections at 5-σ (GW150914 and GW151226) and a third possible detection at 87% confidence (LVT151012) of the inspiral and merger of binary stellar mass BH systems (The LIGO Scientific Collaboration *et al.* 2016). An electromagnetic (EM) counterpart to the inspiral and merger of a binary BH system is not generally expected and no EM counterpart was detected for any of the observed GW signals (Copperwheat *et al.* 2016).

The next GW breakthrough will be the detection of the inspiral and merger of NS-BH or NS-NS systems. For such mergers we expect various EM counterparts, where the nature of the counterpart depends on the viewing angle (Metzger & Berger 2012). When a NS-BH or NS-NS system merge, the merger ejecta forms an accretion disk, tidal tail and disk wind. The rapid accretion from a disk onto a newly formed BH is thought to power bipolar ultrarelativistic jets responsible for short GRBs and their afterglow, the typical timescale for a short GRB is seconds and hours to days for the associated afterglow (Woosley & Bloom 2006; Nakar 2007; Berger 2014). The more isotropic ejecta can power r-process nucleosynthesis where radioactive decay gives rise to macronova emission, these occur on a day to weeks timescale (Tanvir *et al.* 2013; Berger *et al.* 2013; Tanaka 2016). At later times, approximately a month, the merger ejecta can interact with the ambient medium giving rise to radio flares (Nakar & Piran 2011; Hotokezaka *et al.* 2016).

2. Gamma-ray Bursts and Failed GRBs

Except for two cases (Cenko *et al.* 2013, 2015) we currently detect GRBs and their afterglow by a high energy γ-ray trigger. The variability timescale of the prompt γ-ray emission indicates a dependence for the emiting region, $R_d \propto \Gamma^2$, where R_d is the dissipation radius and Γ the bulk Lorentz factor. The photospheric radius $R_\star$, the point at which the fireball becomes optically thin, can be conservatively estimated by considering the density of electrons associated with a baryonic outflow, $R_\star \propto E^{1/2}\Gamma^{-1/2}$. These conditions require GRBs to be produced in ultrarelativistic jets with $\Gamma \sim 100$.

For jets with $\Gamma << 100$ the dissipation radius falls below the photoshere and the prompt γ-rays would be suppressed. Such a failed GRB will still have a broadband orphan afterglow. The observation of afterglows associated with the relativistic jets from binary NS mergers is currently biased by the requirement of a high energy γ-ray trigger, GW triggered searches may reveal a hidden population of low-Γ merger jets by their on-axis orphan afterglow. Astrophysical jets from other accreting BH systems (e.g. AGN, blazars) follow a simple power law distribution with a negative index, $N(\Gamma) \propto \Gamma^{-a}$, where a is ~ 2 for blazars (Saikia *et al.* 2016). If the jets from mergers follow a similar distribution then failed GRBs would outnumber short GRBs.

3. Monte Carlo

To test whether the on-axis orphan afterglow of a failed GRB from a compact stellar merger would be observable, given a GW detection, a Monte Carlo of 2×10^5 events was generated. The events followed the Wanderman & Piran (2015) redshift and luminosity distribution for short GRBs. The bulk Lorentz factor followed a simple power law with index $a = 1.75$ in the limits $3 \leqslant \Gamma \leqslant 10^3$, and independent of a bursts energy. For details of the Monte Carlo and radiative transfer see Lamb & Kobayashi (2016).

4. Results

We found that for a sample in the range < 300 Mpc, the LIGO/Virgo detection limit for face-on NS-NS mergers, that events below a line given by $\Gamma \sim 16(E_{\rm K}/10^{50}{\rm erg})^{0.15}$ always result in failed GRBs, where $E_{\rm K}$ is the isotropic equivalent kinetic energy. For the parameters used we found that 78% of mergers resulted in failed GRBs; the peak flux and time for the on-axis orphan afterglows from the failed GRBs is shown in figure 1. The model parameters used for the afterglows are: $n = 10^{-1}$ protons cm^{-3}, microphysical parameters $\epsilon_B = 10^{-2}$ and $\epsilon_e = 10^{-1}$, the index of the power-law distribution of random electrons accelerated at shock $p = 2.5$, and the jet half-opening angle $\theta_j = 20°$ ensuring that the jet break time is later than the deceleration time for our sample and is within the limits $16 \pm 10°$ found by Fong *et al.* (2015) for short GRBs. The jet opening angle plays a role only when we estimate the jet break time.

5. Discussion & Conclusion

GW emission is strongest on-axis from a merger event (Kochanek & Piran 1993), thus the probability of an on-axis merger is higher, given a GW detection, than if we consider only the isotropic case (see figure 2). If the Lorentz factor of a jet is correlated with the opening angle, where lower Γ gives a wider half-opening angle (as indicated for long GRBs by Ghirlanda *et al.* 2013), then the rates of on-axis orphan afterglow following a GW trigger will be higher than those given here. By using the rate of short GRBs

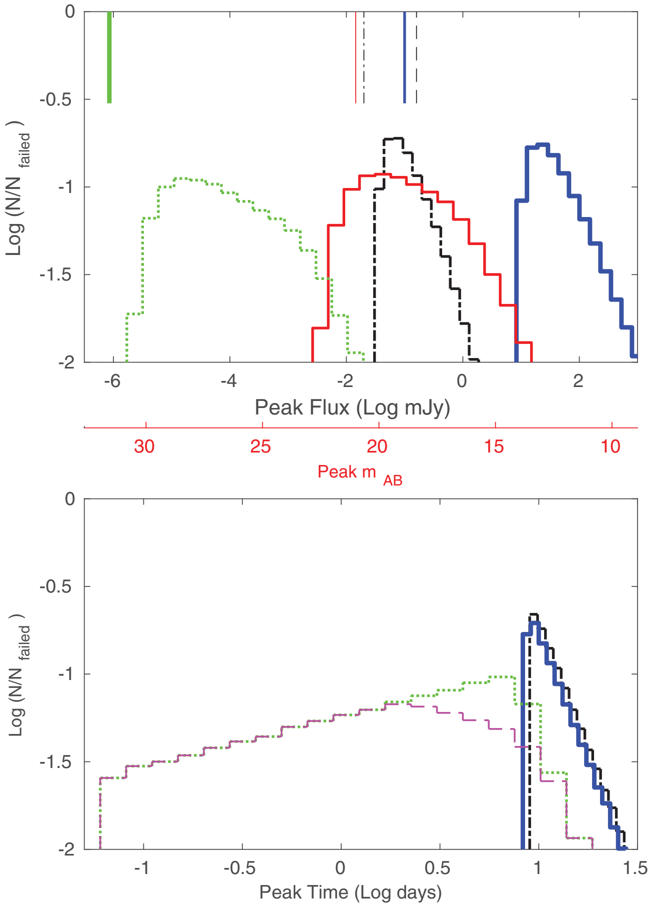

Figure 1. The peak-flux (top panel) and peak-time (bottom panel) distribution of on-axis orphan afterglow from failed GRB events within 300 Mpc. The distributions are normalized by the total number of failed GRBs. X-ray (dotted green line), optical (thick solid red line), radio 10 GHz (thick solid blue line) and radio 150 MHz (thick dash-dotted black line). The vertical lines in the top panel indicate the sensitivity limits of telescopes (thick green XRT, thin red optical ~ 2 m, dash-dotted SKA1-Low, and dashed 48 LOFAR), and the dashed magenta line in the bottom panel shows the distribution of bright events $m_g \leqslant 21$ (Lamb & Kobayashi 2016).

within the LIGO detection volume predicted from the Swift short GRB rate by Metzger & Berger (2012), 0.03 per year, and considering the all sky rate - we find approximately 2.6(26) on-axis orphan afterglows from NS-NS(NS-BH) mergers per year when assuming a jet half-opening angle of 20°.

EM counterparts to GW emission from NS-NS and NS-BH mergers include radio flares, macronova, short GRBs, and on and off axis (orphan) afterglow. A GW triggered search for EM counterparts could reveal a hidden population of low-Γ merger jets from such events and on-axis orphan afterglow of failed GRBs are therefore a strong candidate for EM follow-up searches. The (non)detection of such sources will help constrain the Lorentz factor distribution of such jets (e.g. clustered at high-Γ, a power-law, a log-normal, or multiple populations), and provide constraints on the acceleration process of relativistic jets.

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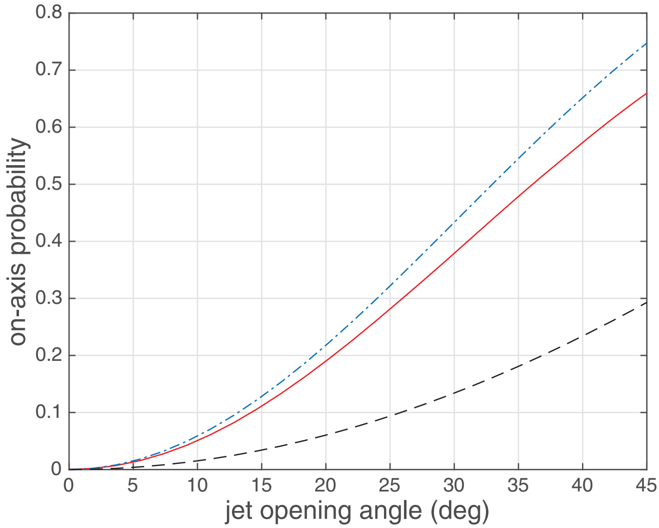

Figure 2. On-axis probability as a function of a jet half-opening angle θ_j. The beaming factor $f_b = 1 - \cos\theta_j$ (black dashed line), given a GW detection the simple approximation $A^3 f_b$ (blue dash-dot line), and the numerical results (red solid line).

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