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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 $\theta_j = 20^\circ$ ensuring that the jet break time is later than the deceleration time for our sample and is within the limits $16 \pm 10^\circ$ 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

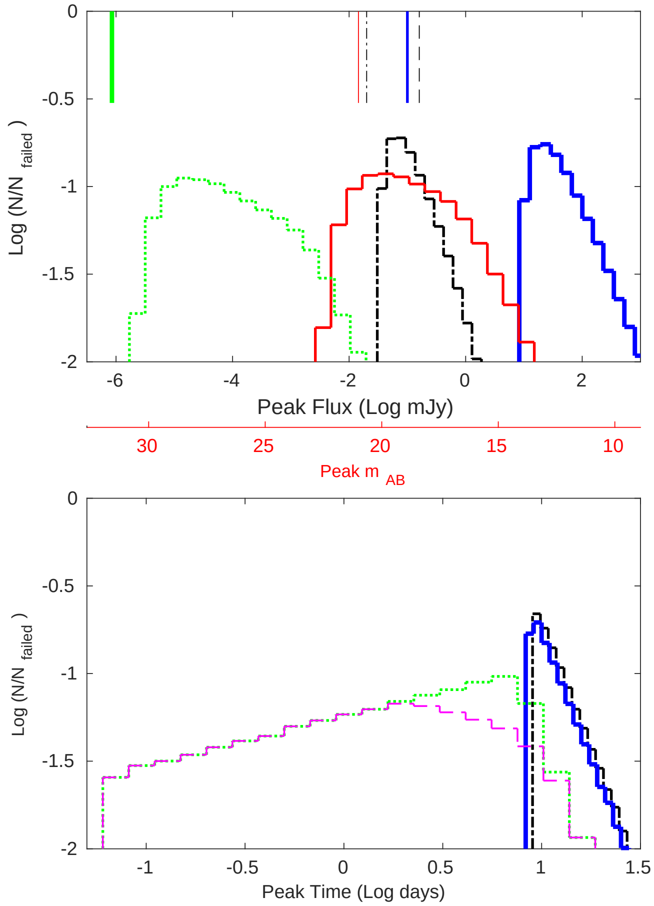

Figure 1. The peak-flux (top panel) and peak-time (bottom panel) distribution of on-axis orphan afterglow from failed GRB events within 300 Mpc. The distributions are normalized by the total number of failed GRBs. X-ray (dotted green line), optical (thick solid red line), radio 10 GHz (thick solid blue 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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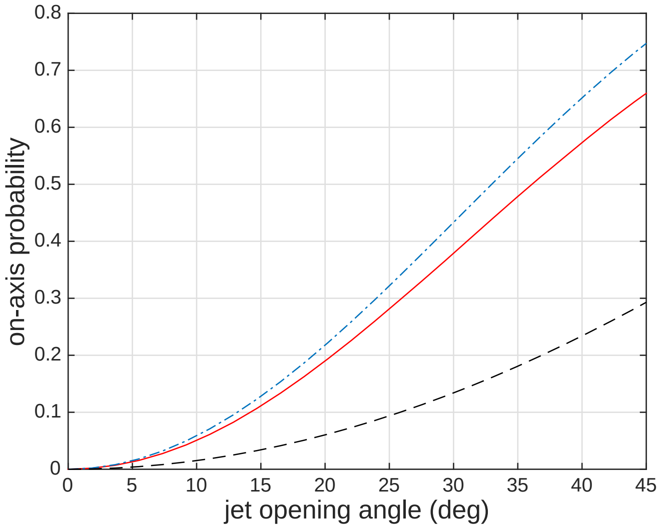

Figure 2. On-axis probability as a function of a jet half-opening angle θ_j. The beaming factor $f_b = 1 - \cos\theta_j$ (black dashed line), given a GW detection the simple approximation $A^3 f_b$ (blue dash-dot line), and the numerical results (red solid line).

References

The LIGO Scientific Collaboration, the Virgo Collaboration, Abbott, B. P., et al. 2016, arXiv:1606.04856

Copperwheat, C. M., Steele, I. A., Piascik, A. S., et al. 2016, MNRAS, 462, 3528

Metzger, B. D., & Berger, E. 2012, ApJ, 746, 48

Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507

Nakar, E. 2007, Phys. Rep., 442, 166

Berger, E. 2014, ARA&A, 52, 43

Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Nature, 500, 547

Berger, E., Fong, W., & Chornock, R. 2013, ApJL, 774, L23

Tanaka, M. 2016, Advances in Astronomy, 2016, 634197

Nakar, E., & Piran, T. 2011, Nature, 478, 82

Hotokezaka, K., Nissanke, S., Hallinan, G., et al. 2016, arXiv:1605.09395

Cenko, S. B., Kulkarni, S. R., Horesh, A., et al. 2013, ApJ, 769, 130

Cenko, S. B., Urban, A. L., Perley, D. A., et al. 2015, ApJL, 803, L24

Saikia, P., Körding, E., & Falcke, H. 2016, MNRAS, 461, 297

Wanderman, D., & Piran, T. 2015, MNRAS, 448, 3026

Lamb, G. P., & Kobayashi, S. 2016, ApJ, 829, 112

Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, ApJ, 815, 102

Kochanek, C. S., & Piran, T. 1993, ApJL, 417, L17

Ghirlanda, G., Ghisellini, G., Salvaterra, R., et al. 2013, MNRAS, 428, 1410