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# ELECTROMAGNETIC COUNTERPARTS TO BLACK HOLE MERGERS DETECTED BY LIGO

Abraham Loeb[1]

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## ABSTRACT

Mergers of stellar-mass black holes (BHs), such as GW150914 observed by LIGO, are not expected to have electromagnetic counterparts. However, the Fermi GBM detector identified of a $\gamma$-ray transient 0.4 s after the gravitational wave (GW) signal GW150914 with consistent sky localization. I show that the two signals might be related if the BH binary detected by LIGO originated from two clumps in a dumbbell configuration that formed when the core of a rapidly rotating massive star collapsed. In that case, the BH binary merger was followed by a $\gamma$-ray burst (GRB) from a jet that originated in the accretion flow around the remnant BH. A future detection of a GRB afterglow could be used to determine the redshift and precise localization of the source. A population of standard GW sirens with GRB redshifts would provide a new approach for precise measurements of cosmological distances as a function of redshift.

## 1. INTRODUCTION

The detection of the gravitational wave (GW) source GW150914 by the Laser Interferometer Gravitational Wave Observatory (LIGO) was interpreted as the merger of a black hole (BH) binary whose members have masses of $M_1 = 36^{+5}_{-4} M_\odot$ and $M_2 = 29^{+4}_{-4} M_\odot$ (Abbott et al. 2016). The GW signal exceeded the background noise level of LIGO for the last $\sim 0.2$ s of the merger when the BH binary separation was shorter than $\sim 10GM/c^2$, where $M = (M_1 + M_2)$. A merger of two BHs in vacuum is expected to have no electromagnetic counterpart. But nature is sometimes more imaginative than we are.

The Gamma-ray Burst Monitor (GBM) on board the *Fermi* satellite reported the detection of a transient signal at photon energies $> 50$ keV that lasted 1 s and appeared 0.4 s after the GW signal (Connaughton et al. 2016). The GBM signal encompasses 75% of the probability map associated with the LIGO event localization on the sky.

Below we explore the possibility that the GW and Gamma-Ray Burst (GRB) signals originated from a common origin, namely a single, rapidly-rotating, massive star.[2] As the core of the star collapsed, it broke into two clumps in a dumbbell configuration. The two clumps collapsed separately into two BHs which eventually merged due to GW emission. The GRB was produced from an outflow generated by the merging BHs or from a jet emanating out of the accretion disk of residual debris around the BH remnant, similarly to the collapsar model of long-duration GRBs (MacFadyen & Woosley 1999; Woosley 1993). The mass accreted during the inspiral must have been a small fraction of $M$ given the good match between the observed LIGO signal and the theoretical GW template for a BH binary in vacuum. The low accretion rate during the inspiral is naturally explained by the clearing of a central cavity that is expected for a circumbinary disk around a binary BH system (Hayasaki et al. 2008; Cuadra et al. 2009; Colpi & Dotti 2009; Kocsis, Haiman & Loeb 2012; Farris et al. 2015).

E-mail: aloeb@cfa.harvard.edu
[1] Department of Astronomy, Harvard University, 60 Garden St., Cambridge, MA 02138

[2] Alternative scenarios in which a neutron star joins a BH binary during its final merger phase or a pre-existing BH sinks to the center of a massive star just around the time when the core of the star collapses to make the second BH, require more fine-tuning in the initial conditions of the system.

## 2. CORE COLLAPSE INTO A BLACK HOLE BINARY

The prevailing collapsar paradigm for long-duration GRBs involves the collapse of the core of a massive star to a single BH (Woosley 1993). In order to produce a GRB outflow, the infalling matter must have a sufficiently high specific angular momentum, $j \gtrsim 3 \times 10^{16}$ cm$^2$s$^{-1}$ (MacFadyen & Woosley 1999), so that its centrifugal barrier lies outside the innermost stable circular orbit (ISCO) around the BH.

To explain the coincidence between a GRB and GW150914 as well as the full temporal window during which LIGO detected a GW signal, we hypothesize that a BH binary formed during the collapse of a rapidly rotating star with an initial orbital radius of $R_b \gtrsim 10GM/c^2 \sim 10^8$ cm (corresponding to a binary separation of $2R_b$ for $M_1 \sim M_2$). The centrifugal barrier of the infalling matter is outside this radius as long as,

$$j = (GMR_b)^{1/2} \gtrsim \sqrt{10}\frac{GM}{c} \sim 10^{18} \text{ cm}^2 \text{ s}^{-1}. \quad (1)$$

Given that the core of the star needs to be more massive than $M \sim 65M_\odot$, the progenitor must be a very massive star with a total mass of hundreds of $M_\odot$ or more. Such stars could form via collision runaway in young dense star clusters (Pan, Loeb & Kasen 2012; Vink 2015), and their mass loss through winds would be reduced at low metallicities. If their final mass falls in the range of 140–260$M_\odot$, they are likely to explode as pair-instability supernovae rather than collapse to BHs (Heger & Woosley 2002), as suggested by the detection of a rare population of unusually luminous supernovae in the nearby universe (Gal-Yam 2012).

Very massive stars of mass $M_\star \gtrsim 100M_\odot$ are dominated by radiation pressure and hence their luminosity is close to the Eddington limit (Bond, Arnett & Carr 1984; Bromm, Kudritzki & Loeb

2001; Loeb & Furlanetto 2013),

$$L_E = 1.3 \times 10^{40} \times \left(\frac{M_\star}{100M_\odot}\right) \text{ erg s}^{-1}. \quad (2)$$

Since their effective surface temperature, $T_s \sim 10^5$ K, has only a weak dependence on mass (Bromm, Kudritzki & Loeb 2001), their radii are approximately given by (Loeb & Furlanetto 2013),

$$R_\star = \left(\frac{L_E}{4\pi\sigma T_s^4}\right)^{1/2} \approx 4.3 \times 10^{11} \left(\frac{M_\star}{100M_\odot}\right)^{1/2} \text{ cm}, \quad (3)$$

where $\sigma$ is the Stepfan-Boltzmann constant. To remain gravitationally bound, the stars must have a specific angular momentum that is significantly lower than

$$j_{\max} = (GM_\star R_\star)^{1/2} = 7.6 \times 10^{19} \left(\frac{M_\star}{100M_\odot}\right)^{3/4} \text{ cm}^2\text{s}^{-1}. \quad (4)$$

Assuming hydrostatic equilibrium and electron scattering opacity, one can show that very massive stars are convectively unstable (see Appendix of Loeb & Rasio 1993). With elastic isotropic scattering of the convective blobs, the star is expected to admit solid body rotation (Kumar, Narayan, & Loeb 1995). Given a rotation frequency $\Omega$, the specific angular momentum would then have the profile $j = \Omega r^2$, with $r$ being the cylindrical radius from the rotation axis. The constraint in equation (1) can therefore be rewritten as

$$\frac{j_s}{j_{\max}} \gtrsim 1.3 \times 10^{-2} \left(\frac{R_c}{R_\star}\right)^{-2} \left(\frac{M_\star}{100M_\odot}\right)^{-3/4}, \quad (5)$$

where $j_s \equiv \Omega R_\star^2$ and $R_c \gtrsim 0.1R_\star \gg R_b \sim 10^8$ cm is the radius of the core that collapses to make the BH binary. We therefore conclude that the progenitor star must be rapidly rotating, not much below its break-up frequency. Such a progenitor could result from the merger of a binary star system with a common envelope.

The appearance of a dumbbell configuration in a collapsing, rapidly rotating system was considered in the literature as a path towards the formation of common envelope massive star binaries through fission (Tohline 2002). For a sufficiently hard equation of state, a rapidly rotating configuration could produce a bar that breaks into two clumps of comparable masses (New & Tohline 1997), consistently with the similarity between $M_1$ and $M_2$ in GW150914. Efficient neutrino cooling or magnetohydrodynamic processes are required to enable rapid collapse of each clump to a BH (Di Matteo, Perna & Narayan 2002; Liu et al. 2015).

The LIGO limits on the spin amplitude of the two BHs are rather weak ($a_1 < 0.69 \pm 0.05$ and $a_2 < 0.88 \pm 0.10$). The final spin of the remnant BH inferred by LIGO is $0.67^{+0.05}_{-0.07}$, but the subsequent accretion of matter could endow it with additional spin and promote the production of a GRB outflow.

A BH binary is expected to clear a central cavity of twice its semi-major axis in the surrounding circumbinary disk (Hayasaki et al. 2008; Cuadra et al. 2009; Colpi & Dotti 2009; Kocsis, Haiman & Loeb 2012; Farris et al. 2015). The delay in filling up this cavity after the BHs' final plunge inside the ISCO would be of order the ISCO dynamical time, which is much shorter than the 0.4 s delay between the GRB and GW150914. For a progenitor star in the mass range $M_\star = 10^2$–$10^3 M_\odot$, most of the observed 0.4 s delay can be accounted for by the extra time it takes the GRB jet to cross the star relative to GWs for a jet Lorentz factor in the range $\gamma \sim 4$–7.

## 3. DISCUSSION

We described a novel mechanism for a prompt electromagnetic counterpart to the merger of stellar-mass BH binaries, such as GW150914. The proposal was motivated by the Fermi GBM detection of a $\gamma$-ray transient 0.4 s after GW150914 (Connaughton et al. 2016). Even if these two signals are unrelated, the possible existence of electromagnetic counterparts to BH mergers at cosmological distances argues in favor of sending LIGO alerts to follow-up observations by radio, infrared, optical, UV, X-ray and $\gamma$-ray telescopes.

The inferred GRB luminosity for GW150914-GBM (at photon energies between 1 keV and 10 MeV) of $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s$^{-1}$ and its measured duration of 1 s (Connaughton et al. 2016) are significantly lower than their typical values in long-duration GRBs (Meszaros & Rees 2014). The observed GRB may be just one spike in a longer and weaker transient below the GBM detection threshold. The weakness of the burst could be attributed to the extended envelope of the very massive progenitor star, from which the GRB outflow just barely managed to escape (Bromberg et al. 2013). For this to work, the BH activity must have persisted for roughly the light crossing time of the star, $\sim 14(M_\star/100M_\odot)^{1/2}$ s. In particular, the low GRB luminosity could have resulted from a broader than usual opening angle of the GRB outflow as it slowed down and widened just before exiting the stellar envelope. A broad GRB outflow brings the added benefit of removing the need for a rare alignment between the line-of-sight and the central axis of the outflow.

The main advantage of the single star origin for GW150914-GBM is that it naturally provides a high infall rate of gas around the merging BHs. The alternative accretion from a long-lived disk (e.g., originating from the tidal disruption of an ordinary star) around the BH binary would be typically limited to the Eddington luminosity (Kamble & Kaplan 2013), which for a binary mass of $M \sim 65M_\odot$ amounts to $\sim 10^{40}$ erg s$^{-1}$, a factor of $\sim 10^9$ lower than the inferred $\gamma$-ray luminosity in GW150914-GBM.

A future detection of a GRB afterglow would allow to determine the redshift and precise localization of the GW source (but see the upper limits in Smartt et al. 2016; Soares-Santos et al. 2016). Since LIGO detected GW150914 only shortly after starting to collect data at its improved sensitivity, it will likely detect many similar events during its future operation. A population of standard GW sirens with GRB redshifts would provide a new path for measuring cosmological distances as a function of redshift to a high precision (Hughes & Holz 2005; Nissanke et al. 2013).

Numerical simulations are required to better characterize the detailed hydrodynamics and neutrino cooling associated with a binary BH formation through a dumbbell configuration during the collapse of the core of a massive star. Magnetic fields could also play an important role in transporting angular momentum and mediating the collapse of the two clumps.

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