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On the possible gamma-ray burst–gravitational wave association in GW150914

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HIGHLIGHTS

- Gravitational wave detected on 09.14.2015 resulted from a merger of two black holes.
- Gamma ray burst that could be related with GW150914 was observed by Fermi satellite.
- Collapsing massive star and a black hole in a close binary could lead to the event.
- GRB was powered by a weak neutrino flux produced in the remnant matter.
- Low spin and kick velocity of the merged black hole are found in our simulations.

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ABSTRACT

Data from the Fermi Gamma-ray Burst Monitor satellite observatory suggested that the recently discovered gravitational wave source, a pair of two coalescing black holes, was related to a gamma-ray burst. The observed high-energy electromagnetic radiation (above 50 keV) originated from a weak transient source and lasted for about 1 s. Its localization is consistent with the direction to GW150914. We speculate about the possible scenario for the formation of a gamma-ray burst accompanied by the gravitational-wave signal. Our model invokes a tight binary system consisting of a massive star and a black hole which leads to the triggering of a collapse of the star's nucleus, the formation of a second black hole, and finally to the binary black hole merger. For the most-likely configuration of the binary spin vectors with respect to the orbital angular momentum in the GW150914 event, the recoil speed (kick velocity) acquired by the final black hole through gravitational wave emission is of the order of a few hundred km/s and this might be sufficient to get it closer to the envelope of surrounding material and capture a small fraction of matter from the remnant of the host star. The gamma-ray burst is produced by the accretion of this remnant matter onto the final black hole. The moderate spin of the final black hole suggests that the gamma-ray burst jet is powered by weak neutrino emission rather than the Blandford–Znajek mechanism, and hence explains the low power available for the observed GRB signal.

1. Introduction

Gamma-ray bursts (GRBs) are extremely energetic, transient events observed from all directions in the sky at high energies. Their known cosmological origin requires the physical process that produces them to be a cosmic explosion of great power. Proposed mechanisms involve the creation of a black hole (BH) in a cataclysmic event. This may either result from the collapse of a massive rotating star, or via the merger of two compact objects, e.g. binary neutron stars or a BH and a neutron star. These two scenarios may produce long (>2 s) or short (<2 s) GRBs, respectively. The so-called 'central engine' of this process is composed of a hot and dense accretion disk with a hyper-Eddington accretion rate (up to a few $M_{\odot}s^{-1}$) near a spinning BH and fast relativistic jets that are launched along the BH's axis of rotation. The angular momentum of the BH is usually invoked as a source of power of jets. In addition, the annihilation of neutrino-antineutrino pairs produced in the nuclear density plasma of the accretion disk can contribute to the jet power (or powering jets). These fast jets produce GRB radiation that ultimately can be observed far away from the central region.

These common scenarios may be related to gravitational wave (GW) emission before and during the action of such an engine. Apart from the strong GW emission produced by the time-varying

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mass quadrupole of an inspiraling and merging compact binary system, several other suggestions were put forward, e.g. neutrino-induced GWs (Suwa and Murase, 2009) or disk precession (Romero et al., 2010). These, however, would be rather weak signals, most probably below the sensitivity limits of current GW detectors.

The recent observation of a GW signal by the two Advanced LIGO detectors on September 14, 2015 (Abbott et al., 2016a) is related to a merger of two BHs in a binary system. Both, the masses and spins of the initial BHs and of the product of the merger were constrained from the amplitude and phase evolution of the observed gravitational waveform. In principle, mergers of binary BHs may be associated with an electromagnetic emission (a GRB), if a sufficient supply of matter for the accretion is involved at any stage of the merger, or after the GW event. As hypothesized in our previous work (Janiuk et al., 2013a), a merger of a massive, rotating star with a companion BH, in a system that evolved from a high mass X-ray binary, may result in the collapse of the star's core. The merger of the collapsed core, which is a newly formed BH, with its companion, would be then the source of a transient emission seen in GWs. The accretion of matter onto the core BH before the merger, and onto the final BH after the merger, would be the source that powers the GRB. Potentially, either one or two GRB signals could be observed, depending on the geometry of the system and the observer's viewing angle. In the following, we elaborate on this scenario in the context of a short duration, hard burst that could be associated with the GW150914 signal.

2. Constraints for the GW150914 GRB

The GRB that could be tentatively related to GW150914 by the observations of the Fermi satellite had a duration of about 1 s and appeared about 0.4 s after the GW signal (Connaughton et al., 2016). The two events were temporally coincident and, within the limit of uncertainty of the two LIGO interferometers and the Fermi detector capabilities to localize the GW source and the electromagnetic source in the sky, could also be associated spatially. The source of the GW was interpreted to be a merger of two BHs of the masses of $36^{+5}_{-4}\ M_{\odot}$ and 29^{+4}_{-4} (Abbott et al., 2016a). The final BH parameters are estimated to be of $62^{+4}_{-4}\ M_{\odot}$ and $0.67^{+0.05}_{-0.07}$ for its mass and spin, respectively. The magnitudes and orientations of the spin vectors of the two initial BHs are weakly constrained. The probabilities that the angles between spins and the normal to the orbital plane are between 45° and 135° are about 0.8 for each component BH; spin magnitudes are constrained to be smaller than 0.7 and 0.8 at 90% probability, for the primary and the secondary BH, respectively. At the same level of probability, the assumption of a strict co-alignment of spins with the orbital angular momentum - a plausible astrophysical scenario in which the BHs are produced from massive stellar progenitors - results in an upper limit of 0.2 and 0.3 for the spins' magnitude of the primary and the secondary BH, respectively (for more details see Fig. 5 and related text in The LIGO Scientific Collaboration and the Virgo Collaboration (2016)). The inferred posterior distribution of the GW150914 parameters disfavors an orientation of the total orbital angular momentum of the system that is strongly misaligned to the line of sight (i.e., the system was likely to be oriented face-on or face-away). Weak constraints on the magnitude and the direction of the initial BH spins of GW150914 make it difficult to provide a meaningful limit on the kick velocity of the resulting BH.

The event took place at a distance of 410^{+160}_{-180} Mpc, corresponding to a redshift of about $z = 0.09$ (assuming the standard cosmological model). The GRB fluence measured by Fermi in the range 1 keV–10 MeV, is of 2.8×10^{-7} erg cm^{-2} which, for the distance inferred from the GW observation, implies that the source luminosity in gamma rays equals to $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg/s.

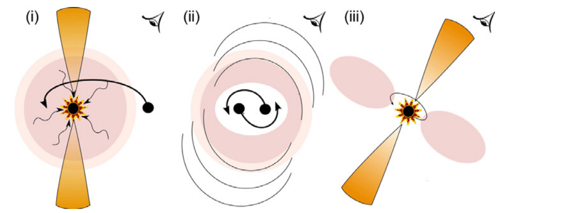

Fig. 1. Cartoon picture of the proposed scenario (stages i, ii, and iii are shown from left to right; see text). The BH in a binary system induces core-collapse of the companion star (i). Fallback accretion of matter form the star's envelope might be accompanied by a weak jet, offset from the line of sight. Next, binary BHs merge inside a circumbinary disk (ii). As a result of the merger, the spin vector of the final BH changes its direction. In the last phase, the remnant matter of the star's envelope is accreted onto the final BH (iii).

3. GRB + GW Scenario

The scenario presented in Janiuk et al. (2013a) describes the collapse of a massive star followed by a binary BH merger. The progenitor, a massive rotating star, is a member of a tight binary system with a companion BH. In order to reconcile a coincidental GW and electromagnetic emission, we assume that after the companion BH entered the star's envelope, the resulting interaction with the stellar core causes its collapse into a second BH. Additionally, some of the angular momentum will be stored in the envelope, as it will be spun up by the transfer of the angular momentum from the companion BH. As a natural consequence, rotationally supported torus is formed in the equatorial plane.

Our model involves three distinct stages of the binary evolution, namely (i) the core collapse and accretion onto the core, (ii) the BH merger inside a circumbinary disk in the interior of the collapsing star, and (iii) further accretion of the remaining matter onto the final BH. Stages (i) and (iii) may create favorable conditions to produce/release energies such as observed in jets, and the resulting GRB signals; stage (ii) is the main engine of the GW signal. The three stages are pictured in Fig. 1.

Both GRB jet types, the one related to the progenitor's collapse and the other to the accretion onto the final BH, may occur unnoticed to an observer if the jets are collimated into narrow cones and the BH spins configuration favors one specific line of sight. However, even if the axis of the first GRB is oriented unfavorably towards the observer (i.e., offset with respect to the line of sight), the second GRB which happens after the merger may be pointing towards the observer. The direction of its axis should be coincident with the spin direction of the final BH, which is the result of the two initial BH spins and the evolution of the system, i.e., it may not be the same as the direction of the first GRB.

In addition, the final BH may receive a natal kick, with a magnitude depending on the BH mass ratio and the configuration of the initial BH spin vectors. Therefore, stage (iii) may in principle lead to the GRB engine leaving its host site and approaching the inner edge of circumbinary disk.

The first phase, core-collapse, can be treated semi-analytically as in Janiuk et al. (2008). In that work, we considered two distinct cases: a homologous accretion of the envelope and a large increase of the subsequently created BH mass, or the accretion through a torus, and wind outflow. The latter, if supported by a centrifugal force and driven magnetically, can take away up to about 75% of the mass (Janiuk et al., 2013b) from the rotating torus. Nevertheless, in the current context, we suppose that no massive wind was associated with GW150914, since the observations do not support a presence of large amounts of mass in the vicinity of the GRB there. We also do not concentrate here on the details of this phase, because the GRB was detected *after* the GW signal. In the following, only these two phases are considered in detail.