GRAVITATIONAL-WAVE OBSERVATIONS MAY CONSTRAIN GAMMA-RAY BURST MODELS: 
THE CASE OF GW150914–GBM

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Received 2016 July 6; revised 2016 August 3; accepted 2016 August 4; published 2016 August 18

ABSTRACT

The possible short gamma-ray burst (GRB) observed by Fermi/GBM in coincidence with the first gravitational-wave (GW) detection offers new ways to test GRB prompt emission models. GW observations provide previously inaccessible physical parameters for the black hole central engine such as its horizon radius and rotation parameter. Using a minimum jet launching radius from the Advanced LIGO measurement of GW 150914, we calculate photospheric and internal shock models and find that they are marginally inconsistent with the GBM data, but cannot be definitely ruled out. Dissipative photosphere models, however, have no problem explaining the observations. Based on the peak energy and the observed flux, we find that the external shock model gives a natural explanation, suggesting a low interstellar density ($\sim 10^{-3}$ cm$^{-3}$) and a high Lorentz factor ($\sim 2000$). We only speculate on the exact nature of the system producing the gamma-rays, and study the parameter space of a generic Blandford–Znajek model. If future joint observations confirm the GW–short-GRB association we can provide similar but more detailed tests for prompt emission models.

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

1. INTRODUCTION

With the first detection of gravitational waves (GWs), we entered a new era in astrophysics (Abbott et al. 2016a). Electromagnetic counterparts are crucial for establishing the astrophysical context for the GWs and also for a more accurate localization to aid subsequent follow-up (Connaughton et al. 2015). Gamma-ray burst (GRB) progenitors (see Meszaros & Rees 2014; Kumar & Zhang 2015 for reviews) have been the leading candidates for sources of GWs (Kobayashi & Mészáros 2003; Corsi & Mészáros 2009). The most widely considered GW sources are compact binary mergers with components stemming from a combination of neutron stars (NS) or black holes (BH). Other than BH–BH mergers, substantial radiation is expected to accompany the GW signal, and indeed, the leading candidate for short-hard GRBs are merging NSs (Paczynski 1986; Eichler et al. 1989). The GW 150914 event is best explained by the merger of two $\sim 30 M_\odot$ BHs. Fermi/GBM detected a tantalizing counterpart, GW 150914–GBM (Connaughton et al. 2016), consistent with a weak short GRB, broadly consistent with the GW location and temporally coincident with the GW signal (offset of $\Delta t_G \sim t_{GRB} - t_{GW} = 0.4$ s). We note however that while the Advanced LIGO and GBM locations are consistent, they both span a significant portion of the sky ($\sim 600$ square degrees for Advanced LIGO at 90% confidence level and $\sim 3000$ square degrees for GBM at 68% confidence level). This observation potentially marks the beginning of multi-messenger astrophysics.

In this paper we assume that the weak GBM burst is a GRB (we refer to it as GW 150914–GBM) associated with GW 150914, and investigate its implications for the physical parameters of the system and for its surroundings. This joint electromagnetic (EM), GW observation has already been addressed in a significant number of early studies covering aspects of EM energy extraction from a binary BH system and its surroundings (Fraschetti 2016; Li et al. 2016; Loeb 2016; Perna et al. 2016; Yamazaki et al. 2016; Zhang 2016).

INTEGRAL/ACS observations (Savchenko et al. 2016) set a constraining upper limit in terms of the source fluence in the ACS energy range (above $\sim 75$ keV). The uncertainties on the GBM spectral parameters and on the direction of the possible source, however, weaken any tension between the two measurements (for details, see Section 3.3 of Connaughton et al. 2016). Nonetheless, we emphasize that the association between the GBM event and GW 150914 might have occurred by chance. However, because the false alarm probability of the two events being associated is $P = 2.2 \times 10^{-3}$ (Connaughton et al. 2016), we will assume a common origin and venture to discuss the implications for the GRB emission models.

There has been considerable uncertainty in the GRB prompt emission model parameters, such as the compact object mass and rotation rate. For the first time, however, we can use realistic input parameters for modeling the BH central engine, because the GW observations yield these parameters to a precision that was previously unavailable. We calculate, to the extent that the gamma-ray observations allow, the constraints on the usual GRB models that can be placed.

Jets and BH central engines are thought to be ubiquitous in GRBs. Energy released from the central engine becomes collimated either by magnetic stresses or the ram pressure of a progenitor star. The initial dynamics of the jet are determined by the launching radius, the size of the base of the jet, where the Lorentz factor of the matter, which eventually produces the GRB, is around unity. In other words, the launching radius ($R_0$) is the characteristic size of the volume in which energy is deposited. It is beyond this radius that the jet starts to accelerate.
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Current methods of determining the launching radius rely on the blackbody components in the GRB spectrum (Pe’er et al. 2007). Larsson et al. (2015) found that the launching radius for GRB 101219B is approximately 10 times the horizon radius. This suggests the launching radius is defined by the scale of the BH central engine rather than larger scales (\(>10^7\) cm) such as the progenitor star (e.g., in the case of reconnection shocks; Näslund 2012). Even considering substantial progress in jet modeling, the launching radius is one of the least well-constrained physical parameters of the fireball model. The GW observations can determine the parameters of the resulting BH and give a strict lower limit on the launching radius.

In the next section we list the observational properties of the GW and \(\gamma\)-ray event. In Section 3, we briefly speculate on the parameters of the gamma-ray emitting system. In Section 4, we mention GRB radiation models in the context of this source. Finally, we discuss our results in Section 5. For the quantity \(Q\), we use the \(Q_e = Q/10^4\) scaling notation in cgs units, and the physical constants have the usual meanings.

2. OBSERVATIONS

2.1. Gravitational Waves

The energy released in GW 150914, \(E_{GW} \approx 3 \cdot 10^{49}\) erg, is comparable to the isotropic equivalent energy release of very bright GRBs. The final mass of the merged BH is \(M_{BH} = 62 \pm 4 \cdot 10^5\) \(M_\odot\), and its rotation parameter is \(a = 0.67^{+0.05}_{-0.07}\) (Abbott et al. 2016a). The gravitational radius of a 62 solar mass BH is \(R_G = G M_{BH}/c^2 = 9.2 \times 10^6\) cm; the horizon radius is \(R_H = (1 + \sqrt{1 - a^2})R_G = 1.6 \times 10^7\) cm.

The innermost stable orbit, which we later associate with the launching radius of the jet, is at \(R_0 \approx f_1(a) R_G = 3.2 \times 10^7\) cm, \(f_1(a) = 0.67\), \(f_2(a) = 2 - a + 2(1 - a)^{1/2}\).

GRB models usually invoke jets emitted along the rotation axis of their progenitor BH. Due to Doppler boosting we can further assume our viewing angle is within the opening angle of the jet, otherwise the EM emission would be highly suppressed (essentially undetectable). The most favorable configuration for both GW detection and jetted emission is for the case when we view the binary system perpendicular to the rotation plane. The GW signal does not have a strong dependence on the viewing angle. All things being equal, the difference in GW signal-toneoise from a face-on to an edge-on configuration is a factor of \(\sqrt{8} \approx 2.8\). Due to a known degeneracy between the inclination angle and distance (Cutler & Flanagan 1994; Abbott et al. 2016b), basically all the inclination angles are allowed by GW data. The observed \(\gamma\)-rays however suggest that we see the system close to face-on.

2.2. Gamma-Rays

GBM detected a weak source with duration of \(T_e \approx 1\) s, which, at the time of the GW trigger was in an unfavorable position for the GBM detectors. Careful analysis however reveals a source with parameters consistent with a short GRB (Connaughton et al. 2016).

GBM count spectra were deconvolved with detector response matrices for multiple positions within the joint GBM/LIGO localization region. The resulting fit is mostly consistent with a hard power law, with photon index \(\alpha_{PL} = -1.40^{+0.18}_{-0.24}\). This power-law index is consistent with other weak short GRBs that have been detected by GBM that can only be fit by a power law due to their low flux. The median (mean) value for the PL index for all weak GBM short GRBs is \(-1.36\) (\(-1.40\)). The luminosity in the 1 keV to 10 MeV range, which is a good approximation for the bolometric luminosity, is \(L_{obs} \approx 2.3 \times 10^{50}\) erg s\(^{-1}\).

Hints for a possible cutoff energy come from one of the positions on the initial localization annulus, where it was possible to constrain a more physically realistic Comptonized spectrum (power law with exponential cut off):\(^7\)

\[
\frac{dN_{ph}}{dE} \propto \begin{cases} 
E^{\alpha_{Comp}} \exp\left(-\frac{E}{E_{pk}}\right), & E < E_{pk} \\
0, & E \geq E_{pk}
\end{cases}
\]

Short GRBs are typically well fit using this model, with high peak energies and a steep spectrum above the peak energy. The assumed source position however is not compatible with the relative count rates measured in the 14 GBM detectors, and is excluded at the 90% confidence level by the joint GBM-LIGO localization.

The event is too weak to confidently constrain more than two spectral parameters. Since the best-fitting power-law spectrum is ultimately unphysical because it implies an infinite amount of liberated energy, we carry out Monte Carlo simulations to evaluate the ranges of the Comptonized model parameters allowed by the observations. The count spectrum has a maximum at roughly 1 MeV, indicating that the spectral peak lies at that energy or above it, regardless of the details of spectral fitting. We substantiate this claim by fixing the photon index at the mean value for short GRBs, \(-0.42\) for a model with an exponential cutoff above \(E_{pk}\), and generate a distribution of amplitudes and peak energies for all positions along the localization arc. We find that in 94.6% of cases, the peak energy exceeded 1 MeV indicating a high peak energy event similar to short GRBs (Figure 1, right). We also carry out a simulation where we fix the peak energy at 1 MeV and fit the amplitude and the photon index (Figure 1, left).

\(^7\) We note that while the cutoff energy could be constrained, the cutoff power-law model is not statistically preferred over a power-law spectrum.
3. RADIATION FROM A STELLAR MASS BH MERGER

Significant EM energy release from a binary BH merger is unexpected. The dispersion length of GWs is much larger than the curvature radius associated with material surrounding the merger in any conceivable scenario (e.g., Misner et al. 1973), thus no significant energy transfer is expected from GW to matter. Also, no obvious debris are expected from the BH–BH merger that can aid the energy release, similar to a BH–NS or NS–NS mergers (see however Li et al. 2016; Loeb 2016; Murase et al. 2016; Perna et al. 2016; Yamazaki et al. 2016).

In principle, a fraction \( f_s(\alpha) = 1 - \sqrt{1 + \sqrt{1 - \alpha^2}} / 2 \approx 6\% \) of the BH energy is available for extraction from a rotating BH. This corresponds to \( E = 62 f_s(0.67) \times 10^{42} \) erg, which is four orders of magnitude more than the observed energy release. Methods of tapping energy from the merged BH include neutrino-driven disks (Zalamea & Beloborodov 2011) and the Blandford–Znajek (BZ) process (Blandford & Znajek 1977; see however Lyutikov 2016).

More conventional models for energy release in a BH system can be put forward as follows. In the GW 150914 progenitor system about 5\% of the initial total mass was radiated away as GW. Because of the reduced central mass, orbits of the fluid elements in a disk around the final BH will be modified (Bode & Phinney 2007), possibly producing shocks. Furthermore, the final BH will experience a kick associated with the anisotropic emission of GWs (Farris et al. 2011). The angular momentum vectors of the binaries were parallelized by interaction on long timescales, with circumstellar matter implying the kick will launch the BH into the surrounding disk with \( v < 1000 \) km s\(^{-1}\), possibly enhancing the accretion rate. However, these mechanisms yield only \( \lesssim L_E \) luminosities for conditions normally expected around BH mergers (e.g., Lippai et al. 2008).

3.1. Generic Blandford–Znajek Scenario

We forgo pursuing the exact nature of energy release from the BH merger which later results in the electromagnetic counterpart. Specifically, we do not address the provenance of the disk material required to tap the energy of the BH. Given the unexpected association of the GW and EM signals, we outline the generic properties of a BH–disk system launching a jet with opening angle \( \theta_m = 0.1 \), assuming the BZ mechanism. Our aim is to constrain the parameter space for this particular scenario through specific criteria.

We assume the disk height is \( H(R) = R \), but for \( H(R) \approx 0.3 \) \( R \) as required by the model of Perna et al. (2016), the allowed parameter space does not change significantly. We illustrate the system parameters on an \( R_{\text{disk}} - \dot{M} \) plane (see Figure 2). The disk has a viscosity parameter \( \alpha_{\text{ST}} = 0.1 \) (Shakura & Sunyaev 1973).

As a first criterion, we turn to the timescales governing the launch of the putative jet. The accretion timescale, during which a jet of outer radius \( R_{\text{out}} \) is swallowed by a BH, can be calculated from the viscous timescale of the disk. As an example, for \( R_{\text{out}} \approx 2 \times 10^8 \) cm, the accretion timescale is \( t_{\text{acc}} = (7/3\alpha)(R_{\text{out}}/GM_{\text{BH}})^{1/2} \approx 10^4 \) s. The central engine timescale (the accretion timescale in our example; Zhang et al. 2009) can be constrained to be at most the observed duration or \( t_{\text{acc}} \lesssim 1 \) s (Aloy et al. 2005). This constraint will carve out a region in Figure 2 to the left of the \( t_{\text{acc}} = 1 \) s or \( R_{\text{out}} = 2.3 \times 10^8 \) cm line.

![Figure 2. Disk parameter space constrained by the observations. The cross-hatched rectangle marks the approximate allowed outer disk radius and mass accretion rate.]
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The numerical scaling values for the observed luminosity and the calculated launching radius respectively. $R_{\text{sat}} = R_0 \Gamma \approx 3.2 \times 10^{10} (R_0/R_g) \Gamma T_4 \Gamma_4 \text{ cm.}$ The fact that the actual Lorentz factor, $\Gamma \gtrsim 1000$, is likely larger than $\Gamma_T$ (see e.g., Section 4.3) suggests the photosphere occurs in the acceleration region. For example, for $\Gamma = 10^3$, we have $R_{\text{phot}} \approx 3 \times 10^7 \text{ cm} < R_{\text{sat}}$. The observed temperature of an expanding fireball at its photosphere (occurring in the acceleration phase) can be calculated as $T_0 \approx (L/4\pi R_0^2c)^{1/4} \approx 1/(L/L_{\text{obs}})^{1/4} (R_0/R_g)^{-1/2} \text{ MeV.}$ The maximum attainable peak energy of a spectrum with temperature $T$ (Li & Sari 2008; Fan et al. 2012; Zhang et al. 2012):

$$E_{\text{pk}} \lesssim 3.92 \times kT_0 \approx 0.6 \left(\frac{L}{L_{\text{obs}}}\right)^{1/4} (R_0/R_g)^{-1/2} \text{ MeV.}$$

The 3.92 factor indicates that the $E_{\text{pk}}$ is the peak in the $vF_v$ representation. Since we know $R_0$, the smallest possible launching radius from the GW observations, we know Equation (5) is a strict upper limit for the temperature of the non-dissipative photosphere. The measured peak can reach the upper limit in Equation (5) in the case where the photosphere occurs in the acceleration region. In this case the comoving temperature is proportional to $R^{-1}$ and the increase of the Lorentz factor (xR) compensates for the decrease to yield a temperature of $T_0$.

The peak energies of the simulated set of Comptonized spectra violate this limit (see Figure 1, right) in an overwhelming number of cases. Thus, even with the uncertainties of the spectral parameters, we consider this model is not favored by the data; however, we cannot rule it out.

A more sophisticated class of models for the GRB prompt emission are dissipative photosphere models (Rees & Mészáros 2005). In these models, energy is liberated while the flow is still optically thick through, e.g., neutron–proton collisions (Beloborodov 2010) or magnetic reconnection (Giannios & Spruit 2007). There are no simple criteria for meaningful comparisons with data for GW 150914–GBM. For these models, in general terms, the peak energy is not constrained by the expression in Equation (5) and can reach substantially higher values ≤ 20 MeV (Beloborodov 2013). For example, for the observed luminosity of $2.3 \times 10^{49} \text{ erg s}^{-1}$, the maximum achievable peak energy is around ~10 MeV both for magnetic-field-dominated outflows and for baryon-dominated cases as well (see Figure 2 of Veres et al. 2012).

4.2. Internal Shocks

Internal shocks can occur in unsteady relativistic outflows (Rees & Mészáros 1994) where a faster shell catches up with a slower one. The colliding shells produce shocks that accelerate electrons and amplify the magnetic field, and in turn the electrons emit synchrotron radiation. This process can tap the relative kinetic energy of material ejected at different times from the central object.

The radius of internal shocks can be calculated as $R_{\text{IS}} \approx 2 c \Gamma_{\text{r}}^2 dt$, where $dt$ is the variability timescale. For short GRBs, the average $dt \approx 10^{-2} \text{ s}$ (MacLachlan et al. 2013). The detailed temporal structure of the gamma-ray lightcurve could not be determined by the GBM data for this weak event. Based on the GW observations, however, we can put a lower limit on the variability timescale that is the dynamic time $t_{\text{dyn}} = \frac{R_{\text{obs}}}{\Gamma v}$.

4. RADIATION MECHANISMS

Focusing on the gamma-ray signal, it has both spectral and temporal properties consistent with the prompt emission of a short GRB. The observed luminosity is ~10 orders of magnitude larger than the Eddington luminosity, indicating the gamma-ray source has likely experienced relativistic expansion. In the GRB fireball scenario the jet Lorentz factor is expected to go through the acceleration phase, starting from the radiation from a jet with half opening angle $\theta_{\text{jet}}$ the observed, isotropic equivalent luminosity is related to the BZ output power as $L_{\text{BZ}} = L_{\text{obs}} \theta_{\text{jet}}^2/2 = 200(\theta_{\text{jet}}/0.1)^{-2} L_{\text{BZ}}$. Thus, the observed isotropic equivalent luminosity can be expressed as a function of $M$ (assuming a jet-opening angle, and it is possible to use it to constrain the allowed parameter space of $M$ (see Figure 2). We draw the hatched region by allowing a factor of ~2 around the observed luminosity of $L_{\text{iso}} = 2.3 \times 10^{49} \text{ erg s}^{-1}$. In this scenario, we can constrain the disk mass to $10^{-6} - 10^{-5} M_{\odot}$, and the magnetic field threading the horizon will be ~2 $\times 10^{-5}$ G.

4.1. Photospheric Models

In the relativistically expanding material the location where the Thompson scattering optical depth falls below unity marks the position of the photosphere. This is the innermost radius from which radiation can escape and can be calculated from $R_{\text{phot}} = L/4\pi n_e \Gamma_{\text{phot}}^2$:

$$R_{\text{phot}} \approx \begin{cases} 2.8 \times 10^9 \left(\frac{L}{L_{\text{obs}}}\right) \eta_{\text{g}}^{-3} \text{ cm} & \text{if } R_{\text{phot}} > R_{\text{sat}} \text{ or } \eta \lesssim 1 \Gamma_T \gamma_T \gamma_{\text{r}} \gamma_{\text{r}} \approx 170 (L/L_{\text{obs}})^{1/4} (R_0/R_g)^{-1/4} \text{ is the Lorentz factor} \end{cases}$$

where the Lorentz factor separating the photosphere in the acceleration phase ($\eta > \Gamma_T$) and the photosphere in the coasting phase ($\eta < \Gamma_T$). We note here that on the joint GW and EM observations this quantity can be well determined. Henceforth, for brevity we use $L_{\text{obs}} = 2.3 \times 10^{49} \text{ erg s}^{-1}$ and $R_g = 3.2 \times 10^7 \text{ cm}$ to mark the position of the photosphere. Their peak energies of models and in some cases their influence.

$$\begin{align*} &\text{if } R_{\text{phot}} < R_{\text{sat}} \text{ or } \eta \gtrsim 1 \Gamma_T, \\
&4.6 \times 10^9 \left(\frac{L}{L_{\text{obs}}}\right)^{1/4} \eta_{\text{g}}^{-2/3} \eta_{\text{g}}^{-1/3} \text{ cm} \end{align*}$$
Here, $\Delta$ is the width of the shell, which has to be greater than $R_0$. Note that here, the electron and magnetic-field equipartition parameters $\epsilon_e$ and $\epsilon_B$ are normalized to 1.

With the spectral peak constrained to be reliably above 1 MeV, the above derivation suggests the internal shock model has difficulties in accounting for peak energies above 0.5 MeV with a given launching radius. Keeping in mind the large errors on the observed quantities, we can say this model does not naturally explain the observed peak energy; however, just as in the case of the non-dissipative photosphere models, we cannot completely rule it out.

4.3. External Shocks

External shocks were initially proposed (Rees & Meszaros 1992) as a model for GRB prompt emission, but had problems interpreting the strong variability of lightcurves (Kobayashi et al. 1997; see however Dermer & Mitman 1999). On the other hand, it is a very successful model for interpreting the multilight variability of lightcurves (Meszáros & Rees 1997; Chiang & Dermer 1999). Recently, however, claims of external shock origin for the prompt emission have been reported for bursts with smooth, simple light curves (Burgess et al. 2016). External shocks are almost guaranteed to form around a relativistically expanding shell. Here we apply the formalism of the external shock model to constrain the physics of the GW associated GW 150914–GBM event.

A shock front develops as the material from the central engine interacts with the interstellar material (ISM). The timescale on which this occurs is the deceleration time. It marks the time between the material plowed up by the relativistic jet corresponds to roughly $1/\Gamma$ times the mass in the ejecta. For interstellar material of number density $n$, Lorentz factor $\Gamma$, and kinetic energy $E_k$ we have

$$t_{\text{dec}} \approx 0.28 n^{-1/3} \Gamma^{-8/3} (E/E_k)^{1/3} \text{s.}$$

Based on Zhang et al.'s (2007) results for short GRBs, we assume a radiative efficiency $\eta_{\gamma} = E_{\gamma}/(E_k + E_{\text{ph}}) = 0.5$ and obtain $E_k \approx E_{\gamma} \approx L_{\text{obs}} \times 1 \times 1 \approx 2.3 \times 10^{49}$ erg.

The peak flux density of the spectrum can be calculated by adding the individual electron powers and according to (Sari et al. 1998; Gao et al. 2013):

$$F_{\nu,p} = \frac{N_e P_{\nu,\text{max}}}{4\pi D_L^2},$$

where $P_{\nu,\text{max}} = m_e c^2 \sigma T_B/3q_e$ is the single electron synchrotron power, $N_e = 4\pi R_{\text{dec}}^2 n/3$ is the number of swept up electrons, $R_{\text{dec}} \approx 2\Gamma^2 c t_{\text{dec}}$ is the deceleration radius, and

$$B = \sqrt{32\pi \epsilon_B n m_p c^2 \Gamma^2}$$

is the magnetic field in the shocked region. $\epsilon_e$ and $\epsilon_B$ are the electron and magnetic-field equipartition parameters respectively.

The peak energy, corresponding to electron random Lorentz factor of $\gamma \approx 600\epsilon_e \Gamma$ is

$$E_{\text{pk}} = \frac{q_e B \gamma^2 \Gamma^2}{2 \pi m_e c} = 1.1 \left( \frac{\Gamma}{2000} \right)^4 \left( \frac{\epsilon_e}{0.5} \right)^2 \left( \frac{\epsilon_B}{0.5} \right)^{1/2} \text{MeV.}$$

The peak of the external shock radiation occurs approximately at the deceleration time. We know the delay of the EM trigger compared to the GW signal, and we require $t_{\text{dec}} \lesssim \Delta t_{-\text{GW}}$. We draw the deceleration time values on Figure 3 with light blue, and note that our Monte Carlo simulated spectral parameters overwhelmingly result in a deceleration time lower than $\Delta t_{-\text{GW}}$.

We use the measurement of the peak energy (the fact that it is likely above 1 MeV) and the peak flux density from the Comptonized spectrum in the case for the fixed photon index (Figure 1) to place constraints on the particle number density around the progenitor and the Lorentz factor of the outflow. In Figure 3 we show that the two constraints mark a region pointed out the non-trivial shape of the uncertainties on $\Gamma$ and $n$. The peak flux lines (red) are the median and the values corresponding to the FWHM of the $F_{\nu,p}$ distribution. The corresponding magnetic-field strength is $B \approx 20$ G, the radius of peak emission is $R_{\text{dec}} \approx 10^{16}$ cm, and the deceleration time is $t_{\text{dec}} \approx 4 \times 10^{-2}$ s. With these parameters the synchrotron radiating electrons are in the fast cooling regime, which means they lose their energy faster than the dynamical timescale, and this is in line with expectations for the prompt emission. This exercise can be carried out with a wind profile interstellar medium, but for compact mergers the
The up-to-date catalog is located at http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html.

constant density profile is preferred (e.g., Panaitescu et al. 2006).

We note here that in the external shock scenario in its simplest, impulsive energy injection case, the timescale of the GRB duration is also governed by the deceleration time. However, since the derived $t_{\text{dec}} (4 \times 10^{-2} \text{s})$ and the GRB duration ($T_e \approx 1 \text{s}$) differ, we argue that the GRB duration reflects the energy injection timescale, which can be of the order of 1 s, instead of $t_{\text{dec}}$.

We set the microphysical parameters ($\epsilon_e$, $\epsilon_B$) to 0.5. Although we are using this model to constrain the prompt emission, based on afterglow modeling these parameters would in general have lower values. For example, typical afterglow-based values would be $\epsilon_e = 0.1$ and $\epsilon_B = 10^{-2}$. The decrease in the microphysical parameters would have to be compensated by an increase of the Lorentz factor and ISM density (to have the same peak energy and flux), which would result in $\Gamma \sim 5300$ and $n \sim 2.2 \times 10^{-2} \text{cm}^{-3}$.

4.3.1. Efficiency of External Shocks

The above results were presented for an efficiency of 0.5 ($E_k = E_{\text{ph}}$). In the external shock scenario, the radiation taps the kinetic energy of the explosion. Radiative efficiency higher than 50% is unexpected for external shocks. Dermer & Mitman (1999), for example, find that 10% ($E_k = 9E_{\text{ph}}$) efficiency is more consistent with this scenario. In this case, the measured fluence and the peak energy yields a Lorentz factor and external density of $(4 \times 10^{-2} \text{cm}^{-3}, 3300)$. These are even more extreme than the values for 50% efficiency, but consistently point to the low density origin of the binary source. The deceleration time is somewhat larger in this case, $t_{\text{dec}} \approx 8 \times 10^{-2} \text{s}$, but still within the $t_{\text{GRB}} - t_{\text{GW}} = 0.4 \text{s}$.

4.3.2. External Shock Model with an Average Short GRB

Because the peak energy is difficult to constrain for this event we analyze another possible scenario. We take the average photon index and peak energy for a Comptonized spectrum of the short GRB sample for GBM (Gruber et al. 2014). We fit the spectral data and generate amplitude parameters (A in Equation (1)) for the Comptonized spectrum by fixing $\alpha_{\text{short}} = -0.42$, $E_{\text{pk,short}} = 566 \text{keV}$ and using response matrices generated for the 11 positions along the Advanced LIGO localization arc. We get a distribution of peak fluxes for the fixed value of the peak energy. It is possible then to put these parameters on the Lorentz factor density plane (see Figure 4) and deduce that the required density distribution peaks around $5 \times 10^{-3} \text{cm}^{-3}$ with a tail extending to a few $\times 10^{-3} \text{cm}^{-3}$ and the Lorentz factor is $\Gamma \sim 1800$. The deceleration time for this case is $\approx 0.1 \text{s}$, which is again consistently lower than the 0.4 s delay between the GW and EM signal.

5. DISCUSSION AND CONCLUSION

Assuming the binary BH merger is associated with the gamma-ray signal detected by GBM, we have taken the leading prompt emission models for GRBs and applied it to the observations of GW 150914–GBM, aided by the accurately determined central engine parameters through GW measurements. We find that the non-dissipative photosphere and the internal shock models have some difficulty in interpreting the observations, although at this point no model can be definitely ruled out, while a dissipative photosphere model is unconstrained. The external shock model is able to interpret both the high peak energy and the observed flux, yielding constraints on the Lorentz factor of the explosion ($\gtrsim 1000$) and the interstellar density ($\sim 10^{-4} \text{cm}^{-3}$). The lower than usual ISM density is in line with the expectation that the merger takes place far from the birthplaces of its components (e.g., in a galactic halo environment). Furthermore, the low density might be a more general property of the external shock model, which, applied to model afterglow observations of GRBs with $\gtrsim \text{GeV}$ photons (e.g., GRB 090510A), yield similarly high $\Gamma$ and low $n$ (De Pasquale et al. 2010). If we assume spectral parameters characteristic of short GRBs, we still consistently find high $\Gamma$ and low $n$.

Even though our results are not definitive, the strength of such an approach lies in constraining values of the launching radius through GW observations and address EM observations.

Further GW observations with better coverage from GBM will settle if merging BH binaries indeed emit $\gamma$-rays. It is possible, however, that due to observer angle effects, the GRB–GW association will only be settled once a sizable sample of GW and gamma-ray observations has been accumulated. Indeed, GW signals from compact mergers are not strongly dependent on the orientation of the binary while prompt gamma-rays are essentially not expected if we are not inside the jet-opening angle. On the other hand, edge-on systems have on average $1/\sqrt{2}$ the signal of the face-on cases. This results in an increased likelihood that the systems detected by Advanced LIGO are face-on rather than edge-on. By measuring the jet-opening angle for a GRB, we can constrain the available parameter space for the inclination, measured by Advanced LIGO. Furthermore, detailed multwavavelength afterglow modeling (e.g., Zhang et al. 2015) can also constrain the viewing angle.
Once GW observations become routine and their EM counterparts will be readily available, we will be able to address the question of the association of short GRBs with BH mergers on a more solid footing. As an example of investigating GW \textit{150914–GBM} as a member of the short GRB population, Li et al. (2016) argued that it is an outlier on the $E_{\text{pk}}$–$L_{\text{iso}}$ diagram for short GRBs. This may indicate a different progenitor for the GBM event. However, due to the small sample size, the correlation for previous short GRBs is not strong enough for a definite conclusion.

With our current understanding of GRBs, the variability timescale of the GRB light curve can provide a limit on the size of the jet launch. If the GW–GRB association is confirmed, the variability times can be compared to the marginally stable radii resulting from the GW detection. Thus it will be possible to rule out some classes of models more firmly with an analysis similar to the one presented here.

We thank Tyson Littenberg and Michael Briggs for discussions. This study was supported by Fermi grant NNM11AA01A. P.M. acknowledges support from NASA NNX13AH50G.

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