MODELING THE AFTERGLOW OF THE POSSIBLE FERMI-GBM EVENT ASSOCIATED WITH GW150914

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ABSTRACT

We model the possible afterglow of the Fermi Gamma-ray Burst Monitor (GBM) event associated with LIGO detection GW150914, under the assumption that the gamma-rays are produced by a short GRB-like relativistic outflow. We model GW150914-GBM as both a weak, on-axis short GRB and normal short GRB seen far off-axis. Given the large uncertainty in the position of GW150914, we determine that the best chance of finding the afterglow is with ASKAP or possibly the Murchinson Widefield Array (MWA), with the flux from an off-axis short GRB reaching 0.2–4 mJy (0.12–16 mJy) at 150 MHz (863.5 MHz) by 1–12 months after the initial event. At low frequencies, the source would evolve from a hard to a soft spectrum over several months. The radio afterglow would be detectable for several months to years after it peaks, meaning the afterglow may still be detectable and increasing in brightness NOW (2016 mid-July). With a localization from the MWA or ASKAP, the afterglow would be detectable at higher radio frequencies with the ATCA and in X-rays with Chandra or XMM.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GW150914-GBM) – gravitational waves

1. INTRODUCTION

GW150914 is the first gravitational-wave source detected by LIGO (Abbott et al. 2016a), and is the merger of two approximately 30 $M_\odot$ black holes. The merger occurred at a distance of 410$^{+160}_{-180}$ Mpc ($z = 0.09^{+0.03}_{-0.04}$) in the southern hemisphere (Abbott et al. 2016a). Although the merger of two large black holes was not expected to produce a bright electromagnetic signature (Connaughton et al. 2016), the Fermi Gamma-ray Burst Monitor (GBM) found a 1 s increase in gamma-ray emission 0.4 s after the LIGO detection and is located in the same region of the sky (Connaughton et al. 2016). INTEGRAL did not detect an event associated with GW150914 (Savchenko et al. 2016), in contrast to the GBM results.

Assuming the GBM detection is associated with GW150914, it would have an isotropic luminosity of $E_{iso} = 1.8^{+1.5}_{-1.0} \times 10^{50}$ erg, an order of magnitude fainter than any other short GRB analyzed (Wanderman & Piran 2015; Connaughton et al. 2016). Typical short GRB energies are in the range of $E_{iso} = 10^{50}$–$10^{52}$ (Fong et al. 2015). The properties of the Fermi-GBM detection are broadly consistent with a short GRB, although it would be significantly harder than the typical $E_{peak}$–$E_{iso}$ relation for short GRBs (Li et al. 2016). It is possible that GW150914 produced either an underluminous short GRB, a poorly collimated jet, or that it is a short GRB but seen far off-axis, so that the prompt emission directed toward Earth was faint.

GW150914 occurred in the southern hemisphere, but was poorly localized, with the combined LIGO and Fermi-GBM error boxes covering 199 deg$^2$ (Connaughton et al. 2016). This made it very difficult to localize the early, rapidly fading X-ray or optical afterglow. Non-detections have been reported by Swift XRT and UVOT (Evans et al. 2016), the Dark Energy Camera (Soares-Santos et al. 2016), and Pan-STARRS and PESSTO (Smartt et al. 2016).

In the radio, a GRB’s afterglow produces a persistent source, but is initially self-absorbed, taking weeks to months to reach peak luminosity. The best prospect for finding the afterglow would be with a wide-field instrument, such as the Murchinson Widefield Array (MWA), a low-frequency (80–300 MHz) radio array (Tingay et al. 2013), or the ASKAP Boolardy Engineering Test Array at 713.5–1013.5 MHz (Hobbs et al. 2016), both located in Australia. MWA is sensitive to sources brighter than about ~6 mJy before becoming confusion limited at 150 MHz (Tingay et al. 2013), and ASKAP is currently sensitive down to ~3 mJy at 862.5 MHz (GCN 18363). The Australia Compact Telescope Array (ATCA), at 1.1–3.1 GHz, is sensitive to much fainter sources (0.04 mJy in 10 minute integration), but has a much smaller field of view (0.4–0.05 deg$^2$ versus 600 deg$^2$ for MWA and 30 deg$^2$ for ASKAP), making covering the large possible area for GW150914 difficult. It would, however, be able to follow up any candidate afterglow sources.

The best way to determine if LIGO event GW150914 and the Fermi-GBM detection are associated would be to find an afterglow that can be localized to a host galaxy. We model the possible afterglow of GW150914-GBM as a relativistic blastwave expanding into the surrounding medium and emitting synchrotron radiation. For a review of afterglow modeling, see Piran (2004).

The hydrodynamics of a GRB afterglow are typically modeled either using a semianalytic solution for an expanding spherical blastwave, or with direct hydrodynamical fluid simulations. Since a GRB is typically only detected if the Earth is within the jet opening angle and the outflow is initially highly relativistic, a natural model is a spherical, ultra-relativistic Blandford–McKee blastwave (Blandford & McKee 1976), as in, e.g., Granot et al. (1999), van Eerten & Wijers (2009). More accurate semianalytic models of spherical and on-axis jet afterglows have also been used, such an an interpolation between a Blandford–McKee and Sedov–Taylor solution in De Colle et al. (2012a) and an analytic fit to 1D hydrodynamic simulations in Leventis et al. (2012).

Semianalytic models for an off-axis observer are also possible (e.g., Granot et al. 2002; Rossi et al. 2004; Waxman 2004; Morsony et al. 2007; van Eerten et al. 2010), but these
models all assume an ultra-relativistic Blandford–McKee blastwave. Hydrodynamical simulations of on- and off-axis GRB afterglows have been carried out (e.g., Granot et al. 2002; Cannizzo et al. 2004; van Eerten et al. 2010; van Eerten & MacFadyen 2011; De Colle et al. 2012a, 2012b). Although very accurate, full hydrodynamic simulations are computationally expensive and can only be used to directly model a small number of cases.

Our modeling approach, described in Section 2, is to use a semianalytic off-axis blastwave model that smoothly transitions between an ultra-relativistic and non-relativistic expansion, following De Colle et al. (2012a). In Section 3, we use our afterglow code to make specific predictions for possible afterglow light curves of GW150914, given a range of possible model parameters. In Section 4, we discuss under what conditions an afterglow of GW150914 might be detectable.

2. METHODS

We carry out modeling of the afterglow using the Trans-Relativistic Afterglow Code (TRAC). TRAC is able to solve a semianalytic model of the emission of a relativistic fireball with an arbitrary angular distribution of energy and at an arbitrary observer angle (i.e., relative to a jet axis). TRAC is based on the methodology of Granot et al. (1999) and began development for use in Morsony et al. (2009). A full description of TRAC will be published in Morsony et al. (2016, in preparation).

Beginning with an energy distribution and observer angle, at a given observer time, TRAC first calculates the size of the blastwave seen by the observer, along with the values of density, pressure, and Lorentz factor inside this shell. TRAC treats the evolution along each radial direction from the center of the blast as an independently evolving portion of a spherical blastwave (no transverse mixing). Based on the interpolation of De Colle et al. (2012a; Equation (1)), we smoothly transition between the ultra-relativistic Blandford–McKee phase (Blandford & McKee 1976) and the non-relativistic Sedov–Taylor phase. This is important for radio observations, which peak during the mildly relativistic transition phase. At any time, the total energy of a spherical blastwave satisfies

\[
E = R^{3-k}2\Gamma^2\rho_0 c^2 \left[ \frac{8\pi}{17 - 4k} \beta^2 + \frac{(5 - k)^2}{4\alpha_k} (1 - \beta^2) \right]
\]

where \(E\) is the blast energy, \(R\) is the shock radius, \(\Gamma\) is the Lorentz factor of the shock, \(\beta\) is the shock velocity over \(c\), and, for a constant density external medium, \(\rho_0\) is the external mass density, \(k = 0\), and \(\alpha_k = 6.5159\).

Using the three-dimensional grid of fluid values, TRAC then computes the integrated emission from the blastwave as a function of frequency. For the current version of TRAC, we assume the emission is due to synchrotron radiation parameterized by \(\epsilon_e\), the fraction of energy in electrons, \(\epsilon_B\), the fraction of energy in the magnetic field, and \(p\), the spectral index of the electron energy distribution. TRAC solves the radiative transfer equation including local synchrotron cooling and synchrotron self-absorption. All models considered are in the slow cooling regime.

For the models presented here, we assume the shocked gas has an adiabatic index of \(\gamma_{ad} = 4/3\) and that the structure behind the shock front follows that of a relativistic shock, i.e.,

\[
\rho(\chi) = \rho_f \chi^{-(7-2k)/(4-k)}
\]

\[
P(\chi) = P_f \chi^{-(17-4k)/(12-3k)}
\]

\[
\gamma(\chi) = \sqrt{(\gamma_f - 1)^2/\chi + 1}
\]

where \(\chi = 1 + 4(m + 1)(1 - r/R)\gamma_f^2\) is a self-similarity variable, \(\rho_f\), \(P_f\) and \(\gamma_f\) are density, pressure, and Lorentz factor of fluid immediately behind the shock front, and \(r\) is radius at any position behind the shock. For an impulsive explosion with \(k = 0\), \(m = 3\). We also assume that the jet maintains a constant opening angle and does not spread out. Both of these approximations will break down in the non-relativistic limit. In this limit, using a Sedov–Taylor rather than Blandford–McKee internal structure would increase the flux density by up to a factor of 4.5. Allowing the jet to spread reduces the flux density by a factor of 1.5 to 2. The net effect is that our models underpredicts the late-time flux by up to a factor of 2.5.

For all of our afterglow models, we assume the event is located at \(D = 410\) Mpc, with \(\epsilon_e = 0.1\), \(\epsilon_B = 0.01\), \(p = 2.5\) the observer-directed kinetic energy is \(E_{iso} = 1.8 \times 10^{49}\) erg, and the blastwave is expanding into a constant density environment (ISM). We use typical values for the density around observed short GRBs of \(n_H = 10^{-2}\), \(10^{-1}\), and \(10^0\) cm\(^{-3}\) (Fong et al. 2015).

For these values, the self-absorption frequency is initially

\[
\nu_a = 2.39 \times 10^8 E_5^{1/5} n_	ext{H}^{-3/5}\text{Hz}
\]

(Panaiteșcu & Kumar 2000) until the emission peak frequency equals the self-absorption frequency, after which \(\nu_a \propto \tau^{-19/26}\).

3. RESULTS

We model the possible afterglow of GW150914 with two different basic assumptions: (1) that GW150914-GBM is an underluminous short GRB that is isotropic or seen on-axis, or (2) that it is a typical short GRB seen far off-axis, outside the prompt emission cone of the main jet, but with an Earth-directed component that accounts for the Fermi-GBM detection. For each of these assumptions, we model the afterglow with different ISM densities, and, for the off-axis models, different observer angles and jet energies. A full list of model parameters is given in Table 1.

3.1. On-axis, Underluminous Short GRB

For our first set of models, we assume GW150914-GBM is an underluminous short GRB. We assume the GRB is either a beamed jet seen on-axis (\(\theta_{obs} = 0\)) with a half-opening angle of \(\theta_j = 10^\circ\), or as an isotropic explosion (\(\theta_j = 90^\circ\), similar to Yamazaki et al. 2016). We model each case with three different background densities of \(n_H = 10^{-2}, 10^{-1}, \text{and } 10^0\) cm\(^{-3}\).

Figure 1 (top panel) plots the flux density predicted at Earth at 150 MHz (solid lines) and 863.5 MHz (dashed lines) for the isotropic cases. For GW150914, the vertical dotted line corresponds to 2016 July 10, the approximate publication date of this Letter. Higher external density produces a brighter radio flux. It does not change the time of the peak flux, except for the highest-density model at 150 MHz, where the blastwave is still...
optically thick. In this case, the peak is delayed from 3 weeks after the GRB to 7 weeks.

In the jetted cases (Figure 1, bottom panel), higher densities lead to an earlier time of peak emission, as the blastwave decelerates faster and the edge of the jet becomes visible at an earlier time (the jet break). The highest-density model is again impacted by opacity at 150 MHz, limiting its peak flux density to 0.03 mJy and creating a plateau lasting until about 1 day.

All on-axis and isotropic cases produce a low flux, reaching at most 0.23 mJy at 150 MHz (0.34 mJy at 863.5 MHz) for the spherical high-density model at about 50 days (7 days) after the LIGO event. This would be a very difficult detection for any low-frequency radio array due to source confusion (Tingay et al. 2013).

### 3.2. Off-axis Normal Short GRB

Next, we model the afterglow as arising from an off-axis short GRB with a range of typical short GRB parameters. In all cases, we assume a jet with a half-opening angle of \( \theta_j = 10^\circ \), consistent with short GRB observations (Fong et al. 2015). LIGO loosely constrains the inclination of the orbital plane of the binary black holes in GW150914, with the most likely value being an inclination of \( \sim 150^\circ \) (LIGO 2016). Assuming the jet axis is aligned with the binary orbital plane, this would place the jet axis \( \sim 30^\circ \) away from our line of sight (\( \theta_{\text{obs}} = 30^\circ \)). We model observer angles of \( 20^\circ, 30^\circ, \) and \( 40^\circ \) to cover a range of possible values. We also model a range of external densities (\( n_H = 10^{-2}, 10^{-3}, \) and \( 10^0 \text{ cm}^{-3} \)) and isotropic energies within the jet to \( E_{\text{iso}} = 10^{51} \text{ or } 10^{52} \text{ erg} \). All off-axis models have an isotropic component with an energy of \( 1.8 \times 10^{49} \text{ erg} \) to account for the Fermi-GBM gamma-rays. In reality, the Earth-directed component need not be isotropic but could be, for example, the wing of a jet that declines rapidly outside of the jet core (Aloy et al. 2005). For simplicity, we consider an isotropic component, responsible for early-time emission, and an off-axis top-hat jet, which creates a secondary peak and dominates late-time emission.

| Model | \( E_{\text{iso}} \) (erg) | \( n_H \) (cm\(^{-3}\)) | \( \theta_{\text{obs}} \) (degree) | Peak Flux\(^a\) (mJy) | Peak Time\(^a\) (weeks) | Peak Flux\(^b\) (mJy) | Peak Time\(^b\) (weeks) |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| iso   | 1.8e49         | 0.1            | 0              | 0.11           | 3              | 0.10           | 1              |
| iso hi| 1.8e49         | 1              | 0              | 0.23           | 7              | 0.34           | 1              |
| iso lo| 1.8e49         | 0.01           | 0              | 0.03           | 3              | 0.03           | 1              |
| on-axis| 1.8e49        | 0.1            | 0              | 0.03           | 0.6            | 0.04           | 0.3            |
| on-axis hi| 1.8e49 | 1              | 0              | 0.03           | 0.2            | 0.10           | 0.2            |
| on-axis lo| 1.8e49 | 0.01          | 0              | 0.03           | 0.7            | 0.02           | 0.4            |
| 51.1-30 | 1.e51        | 0.1            | 30             | 0.34           | 16             | 0.27           | 9              |
| 51.1-20 | 1.e51        | 0.1            | 20             | 0.20           | 22             | 0.12           | 14             |
| 51.0-30 | 1.e51        | 0.1            | 30             | 0.46           | 17             | 1.1            | 5              |
| 51.2-30 | 1.e51        | 0.01           | 30             | 0.10           | 22             | 0.06           | 14             |
| 51.0-20 | 1.e51        | 1              | 20             | 0.35           | 17             | 2.1            | 3              |
| 52.1-30 | 1.e52        | 0.1            | 30             | 2.3            | 38             | 2.4            | 19             |
| 52.0-30 | 1.e52        | 1              | 30             | 2.1            | 56             | 8.2            | 13             |
| 52.1-20 | 1.e52        | 0.1            | 20             | 4.0            | 24             | 6.0            | 10             |
| 52.0-20 | 1.e52        | 1              | 20             | 2.5            | 52             | 16             | 8              |

Notes.

\(^a\) At 150 MHz.
\(^b\) At 863.5 MHz.

Figure 2 (top panel) shows our models for an \( E_{\text{iso}} = 10^{51} \text{ erg} \) jet \( 30^\circ \) off-axis, with three different external densities at 150 MHz (solid lines) and 863.5 GHz (dashed lines). The initial evolution follows the isotropic model cases (see Figure 1). However, after 3 days to 3 weeks, the jet decelerates sufficiently that it begins to become visible to an off-axis observer. High external densities decelerate the jet faster, producing an earlier and brighter peak flux. For an external density of \( n_H = 1 \text{ cm}^{-3} \), the jet is still self-absorbed at 150 MHz when it comes into view, reducing the peak flux and delaying the observed peak until 5 months versus 1 month at 863.5 MHz. The self-absorbed case will also have a hard spectrum (slope of \( \sim 1.6 \)) while the other case have a soft spectrum (slope of \( \sim 0 \)) at 150 MHz. The \( n_H = 0.1 \) and \( 1 \text{ cm}^{-3} \) models reach peak flux densities of about 0.34 mJy and 0.46 mJy 4 to 5 months after the GRB. All three cases would be easily detectable by ATCA at higher frequencies with a good localization.

Figure 2 (bottom panel) shows the results of varying the observer angle for models with \( E_{\text{iso}} = 10^{51} \text{ erg} \) and an \( n_H = 0.1 \text{ cm}^{-3} \). Moving closer to the jet axis increases the observed peak flux and moves the peak earlier in time, from about 1 months to 2 months to 3 months at 863.5 MHz for \( \theta_{\text{obs}} = 20^\circ, 30^\circ, \) and \( 40^\circ \), respectively. At late times, once the entire jet is in view, the declining flux is nearly identical regardless of observer angle.

If the jet energy is \( E_{\text{iso}} = 10^{52} \text{ erg} \) (Figure 3, top panel), the peak time moves later by a factor of two and the peak flux increases by a factor of about 7 relative to models with \( E_{\text{iso}} = 10^{51} \text{ erg} \). With a peak flux density of \( 2-4 \text{ mJy} \) at 150 MHz 6–12 months after GW150914, even a GRB with these parameters would be at most marginally detectable with the MWA, though a source may continue to brighten for several months after the vertical dotted line. The 863.5 MHz flux density is up to 16 mJy and should be detectable by ASKAP. It would also be easily detectable by the ATCA given an afterglow candidate or sufficiently small search region.

At low frequencies, the flux peak occurs near the time when the jet is becoming optically thin. This leads to a large change
in spectral slope near the peak, as seen in Figure 3 (bottom panel). The spectra just before the peak flux is reached become as hard as $F_{\nu} \propto \nu^{-1.6}$ in the high-density case ($F_{\nu} \propto \nu^{-1}$ at medium density) before deaccelerating and ultimately falling to $F_{\nu} \propto \nu^{-0.75}$ at late times. At higher frequencies, the jet becomes optically thin before the peak is reached, creating a less dramatic change in slope, from about $F_{\nu} \propto \nu^{1/3}$ before the peak to $F_{\nu} \propto \nu^{-0.75}$ at late times. The change in spectral slope from hard to soft, particularly at low frequencies, could be used to find promising afterglow candidates for GW150914.

3.3. X-Ray and Optical Afterglow

The modeled R-band optical afterglow of select models are shown in Figure 4 (top panel). At early times, before the relativistic outflow has decelerated significantly, the afterglow is dominated by the Earth-directed energy. Optical emission initially peaks at 100 s at about magnitude 18.1 (19.4) for an external density of 1 (0.1) cm$^{-3}$ and then rapidly fades.

For the off-axis models, there is a second peak when the jet comes into view. This peak is only brighter than the 22nd magnitude for the most optimistic model parameters, e.g., a combination of high external density, high $E_{\text{iso}}$, and small observer angle. However, under such favorable circumstances, the afterglow of GW150914-GRB would have been detectable by Pan-STARRS at several days to months after the LIGO detection, if it was in Pan-STARRS field of view. The late-time optical luminosity is set by the energy of the jet, and by 2016 mid-July even the most optimistic models would be the 26th magnitude. Our optical modeling does not include potential contributions from a non-relativistic supernova or kilonova counterpart.

In the X-ray (Figure 4, bottom panel), the afterglow is as bright as $3.6 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ between 1 and 8 keV and is still brighter than $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ at 1 day in all models. For the off-axis models, the X-rays re-brighten to above $2.6 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, and to as much as $6.3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the brightest case. This is below the detection limit of Swift LMC observations over a portion of the error box of GW150914 (Evans et al. 2016) and just at the detection limit of XMM slew observations (Troja et al. 2016).

At late times, the X-ray flux is mostly set by the $E_{\text{iso}}$ of the jet. At the time this Letter was published, the X-ray afterglow
would be about $4 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ for $E_{\text{iso}} = 10^{51}$ erg and $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ for $E_{\text{iso}} = 10^{52}$ erg. If GW150914 were localized, an afterglow this bright would still be detectable by Chandra or XMM observations.

4. CONCLUSIONS

If GW150914-GBM is associated with the LIGO detection of GW150914, and assuming it is an off-axis short GRB with a relatively bright jet ($E_{\text{iso}} = 10^{52}$ erg), its afterglow would be detectable NOW (2016 mid-July) at 863.5 MHz with ASKAP, but probably not at 150 MHz with the MWA (see Figure 3). Under these conditions, if an afterglow candidate were found, it would be easily observable at higher radio frequencies by the ATCA ($\sim 1$ mJy at 1.4 GHz), in X-rays by Chandra or XMM ($\sim 10^{-15}$ erg cm$^{-2}$ s$^{-1}$), and possibly with deep optical follow-up ($\sim 26$th magnitude in the R-band).

If GW150914-GBM has a more typical short GRB energy of $E_{\text{iso}} = 10^{51}$ erg, it would likely not be detectable by the MWA, reaching a peak flux density of at most 0.6 mJy at 150 MHz. It may still be detectable with ASKAP at 863.5 MHz, where the peak flux density is as high as 2 mJy. However, if an afterglow candidate or sufficiently small error box were identified, such an afterglow would be observable by the ATCA (>0.02 mJy at 1.4 GHz for all models) and possibly deep X-ray observations ($\sim 4 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$) in 2016 mid-July.

If instead GW150914-GBM is a very low luminosity short GRB, either isotropic or beamed, with $E_{\text{iso}} = 1.8 \times 10^{49}$ erg, it was likely never bright enough to be observable without an immediate localization. Only the higher-frequency radio flux would be potentially detectable after the first few hours, at $\sim 0.3$ mJy for a dense external medium.

Given the high rates of black hole mergers inferred from the LIGO detection of GW150914 (Abbott et al. 2016b), if such events do produce short GRBs, future events with slightly more favorable properties should be observable. Having a large GRB jet energy, high external density, jet axis closer to our line of sight, closer distance to Earth, or better initial localization would all favor the detection of an associated relativistic afterglow with follow-up radio, optical, and X-ray searches.
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REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016a, PhRvL, 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016b, arXiv:1602.03842
Aloy, M. A., Janka, H.-T., & Müller, E. 2005, A&A, 436, 273
Bannister, K., Marvil, J., Heywood, I., et al. 2015, GCN Circ, 18363 http://gcn.gsfc.nasa.gov/gcn3/18363.gcn3
Blandford, R. D., & McKee, C. F. 1976, PhFl, 19, 1130
Cannizzo, J. K., Gehrels, N., & Vishniac, E. T. 2004, ApJ, 601, 380
Connaughton, V., Burns, E., Goldstein, A., et al. 2016, arXiv:1602.03920
De Colle, F., Granot, J., López-Cámara, D., & Ramírez-Ruiz, E. 2012a, ApJ, 746, 122
De Colle, F., Ramírez-Ruiz, E., Granot, J., & López-Cámara, D. 2012b, ApJ, 751, 57
Evans, P. A., Kennea, J. A., Barthelmy, S. D., et al. 2016, arXiv:1602.03868
Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, ApJ, 815, 102
Granot, J., Panaitescu, A., Kumar, P., & Woosley, S. E. 2002, ApJL, 570, L61
Granot, J., Piran, T., & Sari, R. 1999, ApJ, 527, 236
Hobbs, G., Heywood, I., Bell, M. E., et al. 2016, MNRAS, 456, 3948
Leventis, K., van Eerten, H. J., Meliani, Z., & Wijers, R. A. M. J. 2012, MNRAS, 427, 1329
Li, X., Zhang, F.-W., Yuan, Q., et al. 2016, arXiv:1602.04460
Morsony, B. J., et al. 2016, in preparation
Morsony, B. J., Lazzati, D., & Begelman, M. C. 2007, ApJ, 665, 569
Morsony, B. J., Workman, J. C., Lazzati, D., & Medvedev, M. V. 2009, MNRAS, 392, 1397
Panaitescu, A., & Kumar, P. 2000, ApJ, 543, 66
Piran, T. 2004, RevMP, 76, 1143
Rossi, E. M., Lazzati, D., Salmonson, J. D., & Ghisellini, G. 2004, MNRAS, 354, 86
Savchenko, V., Ferrigno, C., Mereghetti, S., et al. 2016, arXiv:1602.04180
Smartt, S. J., Chambers, K. C., Smith, K. W., et al. 2016, arXiv:1602.04156
Soares-Santos, M., Kessler, R., Berger, E., et al. 2016, arXiv:1602.04198
The LIGO Scientific Collaboration & the Virgo Collaboration. 2016, arXiv:1602.03840
Tingay, S. J., Goeke, R., Bowman, J. D., et al. 2013, PASA, 30, e007
Troja, E., Read, A. M., Tiengo, A., & Salaterra, R. 2016, ApJL, 822, L8
van Eerten, H., Zhang, W., & MacFadyen, A. 2010, ApJ, 722, 235
van Eerten, H. J., & MacFadyen, A. I. 2011, ApJL, 733, L37
van Eerten, H. J., & Wijers, R. A. M. J. 2009, MNRAS, 394, 2164
Wanderman, D., & Piran, T. 2015, MNRAS, 448, 3026
Waxman, E. 2004, ApJ, 602, 886
Yamazaki, R., Asano, K., & Ohira, Y. 2016, Prog. Theor. Exp. Phys., 2016, 051E01