Multi-messenger Search for GW from LGRBs for CCSNe Collapsar Models
LIGO SURF Program, Summer 2016

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We aim to put quantitative constraints on the fraction of long gamma-ray bursts (LGRBs) associated with Type Ic SNe from observations of gravitational waves (GWs) by introducing a new set of phenomenological waveforms for BH formation and different types of stellar collapse. The usage of collapsar simulations and the phenomenological fallback accretion model for these detectability prospects resulting from LGRBs in association with Type Ic SNe will be considered for GW detectors such as Advanced LIGO and Advanced Virgo, and the Einstein Telescope. In the next few years the improved sensitivity of Advanced LIGO and Advanced Virgo combined with more sophisticated algorithms for identification and parameter estimation of supernova signals will greatly enhance LIGO′s contributions to supernova astrophysics.

I. BACKGROUND

A. GRB-SNe

A type of peculiar and highly energetic supernovae are the broad-line type Ic SNe (SN Ic-BL) that are associated with long-duration gamma-ray bursts (LGRBs). The population of LGRB-SNe isn't correlated with subset of Type Ic SNe, as specifically broad-line Type Ic Sne follow the metallically distribution of star-formation in a general galaxy population [1], but it is worth noting that LGRB associated events do posses unusually broad spectral features [2]. The observations of LGRBs indicate that they occur intrinsically in low-metallicity environments. The distinguishing feature of a GRB-SN that sets it apart from all other SNe is the concentration of significant kinetic energy in relativistic ejecta ($\beta\Gamma \geq 2$). Here, β is the velocity of the ejecta divided by the speed of light and the Lorentz factor $\Gamma = (1-\beta^2)^{-1/2}$. This does not necessarily require that the SN be bright, or even exceptionally energetic, though GRB-SNe often are. It also does not preclude the existence of SNe without GRBs, powered by the same energy source. But to produce a GRB, one needs at least as much energy in relativistic ejecta as is observed in γ-ray and afterglow emission. That is, $E_{Rel} \geq E_\gamma$. The value of E_γ is difficult to measure directly because of the effects of beaming, but in typical bursts, it is around 10^{51} erg. E_{Rel} can be inferred from radio observations at such late times that beaming is no longer important, and is 5×10^{51} erg.

The next step was to recognize and only consider the LGRBs aligned in the direction of the Earth, and therefore a beaming fraction needed to be defined that is given by the burst's beaming angle. There are two widely different, yet accepted, values of 520 ± 85 and 75 ± 25 [3, 4]. The primary difference between the two angle calculations is that one method assumes the existence of a large umber of low-luminosity bursts that cannot be observed except at the closest redshifts, but the other methodology has a consistency between the beaming angle population and that of the *Swift* population. But, this methodology also makes certain simplifications in their the jet structure of the LGRBs and assumes any optical break to be a jet break, which is now known to be classified as a poor approximation. In order to properly constrain and define the jet angle, one of the parameters that is required is the GRB isotropic-equivalent energy release, E_{iso}. This requires the burst redshift to be known, but is not available for most LGRBs. Even when E_{iso} is known, the range in opening angles is fairly broad, and therefore the sample sizes are still insufficient enough to determine a distribution, much less a mean angle.

B. Local Rate of broad-line Type Ic SNe and LGRBs

The fraction of Type Ic SNe that are broad-line derived from the local core-collapse SNe rate is 0.21 ± 0.05 [5]. The local rate of aligned LGRBs is $0.42^{+0.9}_{-0.4}$ [6]. Knowing these statistics, then assuming a semi-nominal beaming factor of 100, this would lead to approximately 1 out of 40 low metallically broad-line Type Ic SNe events that have a potential of giving rise to a LGRB. These results are consistent, given the absence of off-axis LGRB detections in radio surveys of broad-line Type Ic SNe events. Given the 1 out of 40 rate estimated, a minimal sample size of a hundred low metallicity SNe would be required in order to be reasonably confident of detecting an off-axis LGRB. It's important to note that a search performed for LGRBs without any regard to galaxy metallicity would be 5 times less effective in finding a LGRB. A proposal of a radio search that takes into account the low metallicity optimized off-axis LGRB would lead to at least a 90% detection efficiency of off-axis LGRBs.

C. Gravitational Waves from Fallback Accretion onto Neutron Stars

We start by calculating the waveform of GWs from neutron stars that are being spun up by fallback accretion. It is expected that during a CCSNe, a neutron star is born first within the mass ranges from 25 - 40 $M_\odot$, which will usually collapse to a black hole from fallback accretion. Keeping the radius, R, fixed as the mass, M, changes, which is consistent with most equations of state (EoS), except when M is near its maximum value. When $\beta = \beta_{crit}$, then instabilities rise that then produce GWs.

Below is an example mass and strain evolution. The neutron star has $M_0 = 1.3\ M_\odot$ and R = 20 km, and $\eta = 1.0$ for setting M. It is assumed that the neutron star accretes for 100 sec during which $\beta \leq \beta_{crit}$ and no angular momentum is lost. We then set $\beta = \beta_{crit} = 0.14$ and follow the evolution up until M = 2.5 $M_\odot$, at which point the neutron star would collapse to become a black hole. More on this topic will be elaborated on later.

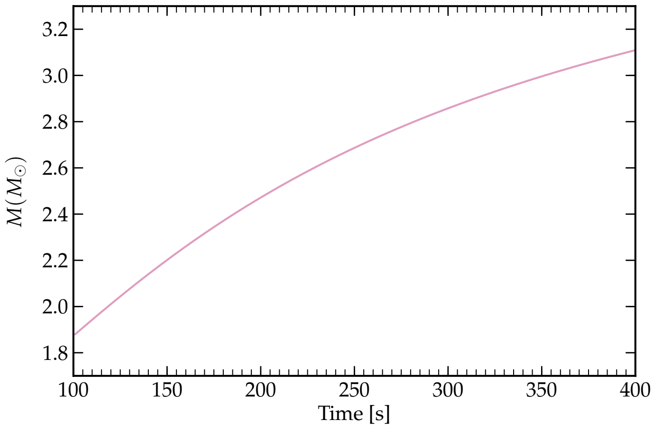

FIG. 1: Example mass evolution, with the neutron star possessing an initial mass, $M_0 = 1.3\ M_\odot$, with a radius, R = 20 km.

The corresponding strain from these gravitational waves as measured on Earth where D is the distance to the source.

D. Collapsar Model

Within the past few years a direct connection has been established between certain core-collapse supernovae (CCSNe) and gamma-ray bursts (GRBs), supporting the collapsar model in which the GRB results from the death throes of a rapidly rotating carbon-oxygen (Wolf-Rayet) star. In more distant GRBs, although the afterglow is normally observed, the supernovae are intrinsically much fainter and hence are often undetected. This confirmed the collapsar model, involving a compact, rotating hydrogen-deficient massive progenitor, i.e. Wolf-Rayet star. Rotation is critically important since the collapsar model involves highly collimated jets produced along the polar axes, arising from a dense, equatorial accretion disc feeding the central black hole. The dense stellar winds from WR stars hinder the direct measurement of rotational velocities, but polarimetry favors negligible deviation from spherical symmetry in most solar metallicity WR stars. An unsolved challenge to evolutionary models involves the requirement of a high angular momentum within the Wolf-Rayet core in the collapsar model. Evolutionary models allowing for magnetic fields involve cores that are efficiently spun down before collapsing, in most models, either due to the shear between the slowly rotating RSG envelope and core, or loss of angular momentum during the WR phase as a result of its high mass-loss rate. These permit the observed rotational rates of young pulsars (e.g. a period of 33 ms for the Crab pulsar) to be reproduced. However, collapsars would require an order of magnitude shorter periods of $\leq$ 2 ms. The key components for a successful LGRB/SN are a compact progenitor with a short light-crossing time of roughly 1 s and fast rotation at the time of collapse. One is the collapsar model, a fast-rotating progenitor fails to explode in its early post-bounce phase and instead forms a black hole, while the in-falling envelope eventually forms a Keplerian disk feeding the hole on an accretion/viscous time scale comparable to that of the LGRB.

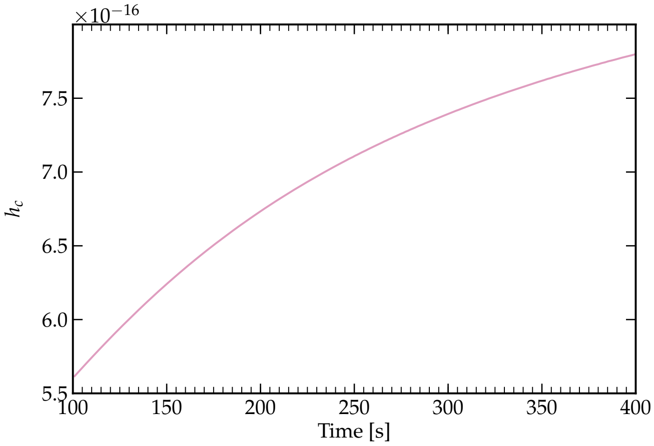

FIG. 2: An example strain amplitude evolution, where the corresponding strain from these GWs is as measured on Earth, where D is the distance to the source.

There are three (3) primary phases associated with approximate approaches in specifically collapsar simulations. In phase 1, GR simulations implement neutrino cooling in which the dynamics after BH formation to the formation of the accretion disk is followed. Phase 2 is primarily concerned with the subsequent evolution of the accretion disk and the outflow formation in the polar funnel region until the jets become mildly relativistic. And,

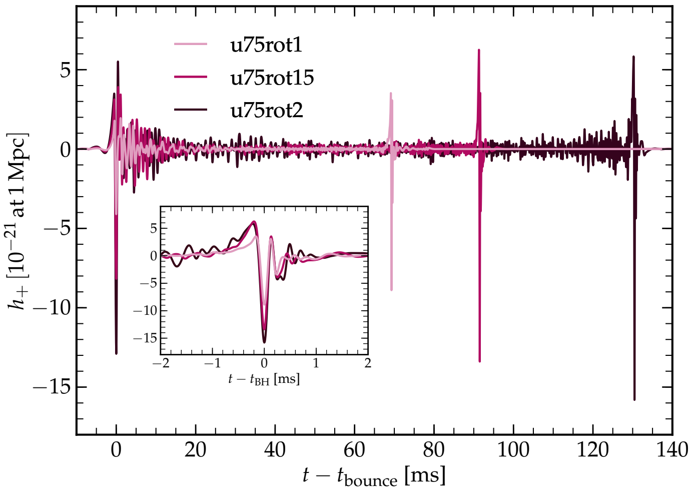

FIG. 3: GW signals, h_+, emitted by the rotating collapsar models as seen by an equatorial observer and rescaled by distance D [7].

phase 3 is mainly concerned with the dynamics from the jet propagation to the breakout from the star by assuming a manual energy input to the polar funnel region.

Ott et al. (2011) [7] were the only ones who extracted the GW signals based on their collapsar simulations (in phase 1). Based on their three-dimensional GR simulations of a 75 $M_\odot$ star using a polytropic EOS, they pointed out that the significant GW emission is associated with the moment of BH formation. A number of semi-analytical estimates have been reported so far that predict a significantly strong GW emission due to possible density inhomogeneities, bar or fragmentation instabilities in the collapsar's accretion torii, and the precession of the disks due to GR effects. Since these GWs from collapsars would be a sure-fire signature of the central engine coinciding with the conventional electromagnetic messengers as well as neutrinos, it will be very important to put forward theoretical predictions of GW signals based on the collapsar simulations, as has been done in the matter of CCSNe.

II. CHALLENGES

The challenges encountered were integrating the 2011 set of collapsar waveforms into the cWB as only one polarization, h_+, that was dependent on distance was provided. Therefore, the correct extrapolation of h_+ as well as converting the distance dependent Dh_+ polarization required careful consideration.

III. REQUIRED RESOURCES

All work will be done on the LIGO Atlas cluster in regards to using the cWB pipeline or in X-pipeline. Otherwise, for the analysis of the collapsar waveform and the construction of the new set of phenomenological models for GWs from the emission of LGRBs from CCSNe will all be done in Python and C.

IV. PROJECT TIMELINE

- June 14th, 2016 - July 1st, 2016 [COMPLETE]
    - Literature Review on multi-messenger searches for GWs from LGRBs from different CCSNe family of waveforms
    - Understand different distance constraints for collapsar family of waveforms specifically for GW detection from LGRBs
    - Introduce a detection prospects study with cWB (Jasmine) and X-pipeline (Sarah)
- July 4th, 2016 - July 22nd, 2016
    - Study different theoretical noise curves for current and future GW detectors
    - Study phenomenological model for GW from fallback accretion onto neutron stars
    - Understand how fallback accretion manifests in EM/neutrino messengers
- July 25th, 2016 - Aug 12th, 2016
    - Construct set of phenomenological waveforms for BH formation and different types of stellar collapse
    - Detectability prospects for GWs from fallback accretion by running cWB and X-pipeline search across relevant parameter spaces with recolored noise (advanced detectors and 3rd generation detectors)

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