The Astrophysical Journal Letters, 884:L16 (5pp), 2019 October 10 https://doi.org/10.3847/2041-8213/ab43e0

Searching for Hypermassive Neutron Stars with Short Gamma-Ray Bursts

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Received 2019 June 23; revised 2019 September 10; accepted 2019 September 12; published 2019 October 7

Abstract

Neutron star mergers can form a hypermassive neutron star (HMNS) remnant, which may be the engine of a short gamma-ray burst (SGRB) before it collapses to a black hole, possibly several hundred milliseconds after the merger. During the lifetime of an HMNS, numerical relativity simulations indicate that it will undergo strong oscillations and emit gravitational waves with frequencies of a few kilohertz, which are unfortunately too high for detection to be probable with the Advanced Laser Interferometer Gravitational-Wave Observatory. Here we discuss the current and future prospects for detecting these frequencies as modulation of the SGRB. The understanding of the physical mechanism responsible for the HMNS oscillations will provide information on the equation of state of the hot HMNS, and the observation of these frequencies in the SGRB data would give us insight into the emission mechanism of the SGRB.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Gravitational waves (678); Neutron stars (1108); Stellar pulsations (1625)

1. Introduction

The observation of the first binary neutron star (NS) merger GW170817 using the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo (Abbott et al. 2017c) and the associated short gamma-ray burst (SGRB) GRB170817A (Abbott et al. 2017a) provided a wealth of information not only about gravitational waves (GWs) but also about the electromagnetic counterpart of the signal (see Abbott et al. 2017b for an early summary), which led the scientific community into the era of multimessenger astronomy with GWs. Although this "golden binary" observation was an extremely fortunate event, we have every reason to be even more optimistic for O3 (the current LIGO/Virgo run that started on April 1st) and for the future. The detection sensitivity has been increased, and in the first months there has been roughly one detection per week of a compact binary coalescence. Furthermore, the Japanese Kamioka Gravitational Wave Detector (KAGRA) is expected to join toward the end of the run, which will result in even better data and sky localization.

The merger of two NSs has long been proposed as one of the possible progenitors of SGRBs (see Berger 2014 for a recent review). Depending on the combined masses of the NSs and on the maximum mass of a neutron star there are, in principle, four possible outcomes to the merger.

1. Prompt formation of a black hole. In this scenario, the total mass is too large to be sustained by rotation of any type and thus a black hole forms on essentially a free-fall time. If the two NSs had nearly equal masses then tidal tails will contain little mass and thus the matter that remains outside the horizon will likely be insufficient to drive a SGRB (see Baiotti et al. 2008 for a discussion of this point). However, if there exist higher-mass versions of the asymmetric double NS binary PSR J1453+1559 (with an estimated pulsar mass of $1.559 \pm 0.005\,M_{\odot}$ and companion mass of $1.174 \pm 0.004\,M_{\odot}$; see Martinez et al. 2015) then potentially there could be sufficient material outside the black hole to power an SGRB.
2. Formation of a hypermassive NS (HMNS), which is defined as a star that is temporarily supported against collapse by strong differential rotation but that is above the maximum mass that can by supported by uniform rotation (Baumgarte et al. 2000). It is expected that within tens to hundreds of milliseconds after the merger the star will lose angular momentum due to the emission of GWs, finally collapsing to a black hole (Shapiro 2000). HMNSs and their surrounding accretion disks are strong candidates for the engines of SGRBs (e.g., Shibata et al. 2006 and Baiotti et al. 2008).
3. Formation of a supramassive NS, which is defined as a star that can be held up against collapse by uniform rotation but that is above the maximum mass for a non-rotating star. Such a star remains stable as long as its angular momentum is sufficient to prevent collapse, and thus can last for seconds to years. In this case, it is expected that the merger will produce a rapidly rotating, highly magnetized NS (i.e., a millisecond magnetar) that can inject energy into the burst (Metzger et al. 2008).
4. Formation of a stable neutron star. The recent determination that PSR J0740+6620 has a mass of $2.17^{+0.11}_{-0.10}\,M_{\odot}$ (Cromartie et al. 2019), combined with the existence of low-mass NSs such as the $1.174 \pm 0.004\,M_{\odot}$ mass of the companion to PSR J1453+1559, suggests that in possibly rare circumstances the combined mass of the two NSs could be less than the maximum mass of a slowly rotating star.

Murguia-Berthier et al. (2014) argued that if the remnant lasts more than 100 milliseconds, the production of a wind due to neutrino emission will produce either a choked jet or a much longer-lasting gamma-ray event than is seen in SGRBs. Thus they argue that SGRBs likely involve rapid (<0.1 seconds) collapse to a black hole, with a possible HMNS phase.[5] Post-

[5] Murguia-Berthier et al. (2014) also left open the possibility of magnetar-driven SGRBs. In that case, they require that the jet be launched <0.1 seconds after the collapse to avoid choking.

merger observations of GW170817 also seem to support an HMNS phase (e.g., Shibata et al. 2017; Rezzolla et al. 2018; Ruiz et al. 2018, and Radice et al. 2018). For example, Metzger & Fernández (2014) proposed that early optical emission days after the merger is a sign of delayed black hole formation: the higher abundance of neutrinos generated in the merger (as compared with the case of a prompt black hole formation and appearance of an event horizon) raises the electron fraction and reduces the formation of lanthanides. The resulting material is rich in elements from the iron group, which have comparatively low opacity and are thought to be responsible for the "early blue bump" seen within the first few days after GW170817 (Abbott et al. 2017b).

Numerical relativity simulations also show that the HMNS should emit strongly in GWs, with a few 1–4 kHz peaks in the signal (see for instance Bauswein et al. 2014; Takami et al. 2014), whose physical origin is not yet completely understood. The detection of these frequencies would provide strong evidence for the HMNS phase and consequently information about the equation of state (EOS) in a hot and magnetized state that will not be probed by studies of GWs from the inspiral (Abbott et al. 2018). Unfortunately, they are in a frequency range that is too high (1–4 kHz) for realistic prospects of detection with current GW detectors, but they will be easily seen in the future with third-generation GW detectors such as the Einstein Telescope (Punturo et al. 2010) and the Cosmic Explorer (CE; Abbott et al. 2017d), which are expected to go online in approximately 15 years.

However, we may not have to wait for third-generation detectors. This signature of an HMNS phase may already be detectable in the electromagnetic counterpart of the signal, as a modulation of the SGRB. This hypothesis can be tested with existing SGRB data from the gamma-ray monitors Burst And Transient Source Experiment (BATSE; Preece et al. 2000), *Fermi* Gamma-ray Burst Monitor (GBM; Meegan et al. 2009), and *Swift* Burst Alert Telescope (BAT; Barthelmy et al. 2005). At the same time, it is important to determine the prospects for detectability with proposed missions such as the Transient Astrophysics Probe (TAP; Camp 2019) and Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (Strobe-X; Ray et al. 2019). Moreover, a detection of the HMNS frequencies in the electromagnetic spectrum in coincidence with a GW detection of a binary neutron star merger could be used to guide a search for the frequencies in the GW signal with a lowered threshold, perhaps allowing their detection with advanced LIGO.

In this Letter we will discuss this observational scenario in Section 2 and present some order of magnitude estimates for the detectability and the statistical significance of the expected SGRB modulation in Section 3. We present our final remarks in Section 4.

2. Modulation of the SGRB

In Figure 1 we display a typical GW signal from a NS–NS merger resulting in a long-lived HMNS. The spectrum can show several complicated features, with at least a couple of clear peaks. The physical interpretation of different features in the spectrum is still not clear, although different correlations have been found; for instance, relating the values of the frequencies of the main peak with the radius of the corresponding $1.6\,M_\odot$ star (Bauswein & Janka 2012), to the tidal coupling constant (Bernuzzi et al. 2015) and to the maximum instantaneous angular frequency of the differentially rotating HMNS (Kastaun & Galeazzi 2015), among other findings.

Given the well-established theory of stellar oscillations (see Kokkotas & Schmidt 1999 for a review), and the general features of the GW frequencies observed in the simulations, it is possible that some of the peaks shown in Figure 1 represent characteristic modes of oscillation modes of oscillation of the HMNS. This is consistent, for instance, with the analysis performed by Stergioulas et al. (2011), who have shown that the main peak is due to the $m = 2$ f-mode (see also Bauswein et al. 2016 and other works).

The emission of an SGRB by a HMNS could in principle carry information from the strong oscillations of the star in this phase. Strohmayer (1992) presented an argument based on relativistic beaming to estimate the surface oscillation amplitude required to produce potentially observable variations in the beaming angle of radio pulsar emission. In more detail, the connection between the NS oscillations and the modulation of the beaming angle of the emission is realized by the strong magnetic field, as the "shaking" of the magnetic field at the surface of the star by surface displacements caused by the stellar oscillations might perturb or modulate the emitting region above the stellar surface (see also Boriakoff 1976). Therefore, the effect of HMNS oscillations could result in a measurable modulation of the SGRB even though the jet has to make its way through the ejecta (see Fenimore et al. 1996 for a study of long complex bursts that can be attributed to the central engine variability).

Therefore, we expect that the high-frequency oscillations of the HMNS in the approximate range 1–4 kHz could be observable, *if the SGRB is emitted during the HMNS phase*. So far, most simulations including magnetic fields have focused on jet formation from black hole remnants. Indeed, Ruiz et al. (2016) found a mildly relativistic outflow (an incipient jet) only after a black hole is formed. The alternative possibility of a (hypermassive) magnetar central engine for the SGRB after a binary NS merger has been relatively little explored, and the relevant timescales for jet formation can be significantly longer than in the black hole + disk case. Current numerical relativity simulations have a common resolution limitation that is not sufficient to fully account for the main magnetic field amplification mechanisms (Ciolfi et al. 2019).

The search for a high-frequency modulation in an SGRB associated with a binary NS merger event could also serve as a probe for the emission mechanism of the burst. The absence of these frequencies in the data could point to the emission of the SGRB as the HMNS collapses to a black hole, which is one possible explanation for the observed ≈ 2 s delay between GW170817 and GRB170817A (Abbott et al. 2017e), but several other possibilities for this delay have been proposed in the literature, such as the time needed for the jet to reach the photosphere and hence be able to emit the SGRB.

Instruments that are suitable for the observation of electromagnetic transients with high timing resolution, such as the currently operating *Fermi* and *Swift*, and concept studies such as TAP and STROBE-X, could detect the modulation in the SGRB caused by the HMNS oscillations nearly in coincidence with future GW detections, enabled by continued increases in LIGO sensitivity.

Additionally, as we argue in the next section, signatures of HMNS oscillations might be present in extant data from

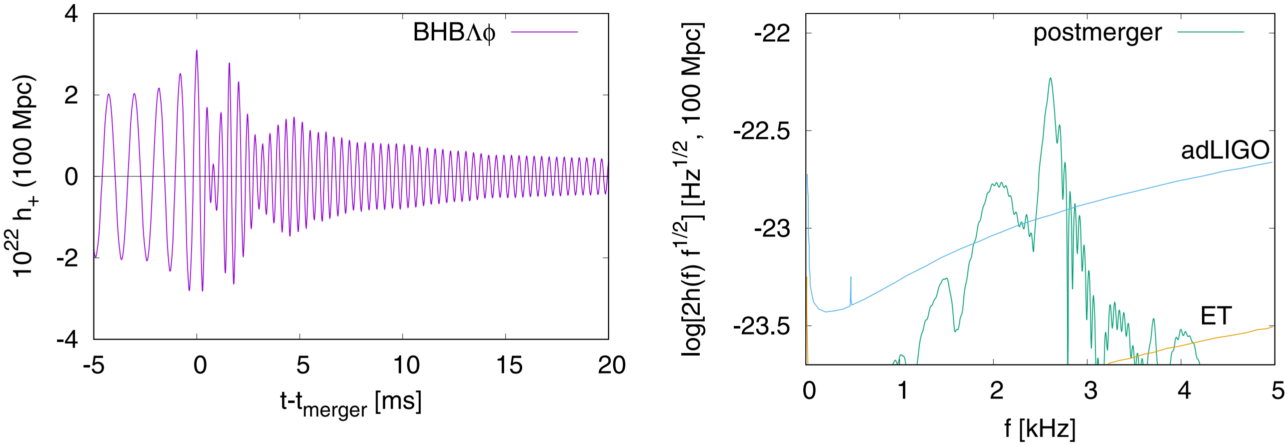

Figure 1. Example of a post-merger GW signal of a long-lived HMNS (left panel) and of its frequency spectrum (right panel), together with the predicted sensitivity curves for Advanced LIGO (Harry & LIGO Scientific Collaboration 2010) and the Einstein Telescope (Hild et al. 2010), both with a signal-to-noise ratio (S/N) = 1. The data are from the $1.35+1.35\,M_{\odot}$ simulation of Radice et al. (2017, top-left panel of their Figure 2), and were kindly provided by David Radice; many other simulations get similar results, e.g., Bauswein & Janka (2012) and Takami et al. (2014). The spectrum shows a couple of clear peaks in a complex structure; at least some of these peaks may be related to oscillations of the HMNS.

especially bright and close SGRBs recorded by BATSE, *Fermi*, and *Swift*. A limited number of studies have searched for periodicity in gamma-ray emission. For example, Kruger et al. (2002) estimated that a 10% modulation amplitude would be detected half of the time with their procedure. However, they found no evidence of periodic modulation in the 400–2500 Hz range from BATSE data on more than 2000 gamma-ray bursts and more than 150 soft gamma-ray repeater flares. Dichiara et al. (2013) also had no detections in their 10–30 Hz analysis of 44 bright SGRBs, but the expected frequencies of HMNS oscillations can be greater than the range that has been searched. More recently, Hakkila et al. (2018) looked at the time-tagged event (TTE) BATSE data, but they were mostly interested in the structure (shape) of pulses of emission and restricted the resolution to 4 ms.

Perhaps the most important point to notice is that the rapid evolution of the differential rotation inside an HMNS will cause the characteristic frequencies to evolve during the burst, and therefore strict periodicity is not expected. Thus a search will require a careful analysis of the expected frequency evolution, which we defer to a later treatment. In the next section we give a broad motivation for why such oscillations are detectable in principle.

3. Detectability and Statistical Significance of the Modulation

Taking as a representative example the dominant frequency peak at $f \approx 2.5$ kHz from the right panel of Figure 1, we can use an approximate expression for the GW strain amplitude from a pulsar of period P at a distance r to calculate the associated surface displacement ΔR needed for an oscillation mode to produce those signals. The GW strain amplitude in this approximation is given by

$$h \approx 4 \times 10^{-23}\epsilon\ (P/1\ \mathrm{ms})^{-2}(100\ \mathrm{Mpc}/r), \tag{1}$$

where we are modeling the star as an ellipsoid with semimajor axes $a > b > c$ rotating around its minor axis, and ϵ is the ellipticity in the equatorial plane, defined as $\epsilon = (a-b)/(ab)^{1/2}$. From this simple model, taking $P = 2/f$ and using the simulation data, we find $\epsilon \approx 8.5 \times 10^{-3}$ and $\Delta R \equiv a - b \approx \frac{\sqrt{2}}{2}\epsilon R \approx 120$ m, assuming a representative HMNS radius of approximately 20 km (Ciolfi et al. 2017).

Motivated by the analysis of Strohmayer (1992) we can propose that, for any arbitrary oscillation mode, the maximum variation possible for the deviation $\Delta\theta$ of the SGRB beam direction will be roughly the slope of the perturbation at the surface, given by the surface displacement ΔR and the wavelength λ of the mode as $\Delta\theta \approx \Delta R/(\lambda/4)$. If the sound speed is the $c/\sqrt{3}$ characteristic of high-energy density matter then $\lambda \approx c/\sqrt{3}f$, and thus $\Delta\theta \approx 7 \times 10^{-3}$.

This deviation must be compared with the larger one between the relativistic beaming angle and the jet opening angle of the SGRB. The relativistic beaming angle is $\theta_b \approx 1/\gamma$, where γ is the relativistic Lorentz factor of the flow, and for typical cases of gamma-ray bursts (GRBs) we have $\gamma \approx 10^2$–10^3, and therefore $\theta_b \approx 10^{-3}$–10^{-2}. Typical values for the jet half-opening angle are $\theta_j \approx 0.1$, but lower values of $\theta_j \approx 0.02$ have also been reported (Jin et al. 2018). As a result, we expect that in the population of SGRBs, HMNS oscillations can produce $\Delta\theta$ up to $\approx 0.4\,\theta_j$. If we estimate that the flux variation should be $\approx \Delta\theta/\theta_j$, this mechanism should produce a noticeable modulation of the signal with tens of percent of flux variation.

We estimate the number n of SGRB photon counts during the lifetime of a HMNS

$$n = F_{\mathrm{SGRB}} \times \Delta T_{\mathrm{HMNS}} \times A_{\mathrm{det}} \big/ E^{\mathrm{obs}}_{\mathrm{peak}}, \tag{2}$$

where we use average values for SGRBs: $F_{\mathrm{SGRB}} \approx 5 \times 10^{-6}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (flux of a moderately bright burst) and $E^{\mathrm{obs}}_{\mathrm{peak}} \approx 350$ keV (observed energy at the peak; Ghirlanda et al. 2009) and $\Delta T_{\mathrm{HMNS}} \approx 0.1$ s (lifetime of an HMNS; Bauswein et al. 2014; Takami et al. 2014). It is worth mentioning here that our approach would be unchanged in the case of a supramassive NS instead of a HMNS; the only difference would be a longer lifetime leading to an even more optimistic estimate. Using values for the effective detector area, n is approximately 1780 for BATSE (Preece et al. 2000), 1250 for *Swift* (Barthelmy et al. 2005), 110 for *Fermi* (Meegan et al. 2009), and $n \approx 790$ for proposed mission TAP (Camp 2019). STROBE-X will have a much larger area than the other detectors (about 4 m^2) but will be limited to lower energies (Ray et al. 2019); however, the Band model for GRB spectra (Band et al. 1993) has a low-energy spectral index α close to -0.4 for SGRBs (see, for instance, Ghirlanda et al. 2009). If we extrapolate this spectrum to 10 keV from the 30 keV lower limit of the BATSE Large Area Detector (LAD) data used by Ghirlanda et al. (2009), we would find typically $n \approx 4230$ counts in STROBE-X.[6]

The expected statistical fluctuation in the photon count is $\sqrt{n}$, which gives a relative fluctuation of approximately 2%–10%. This is significantly lower than the relative fluctuation of up to ~50% that we expect to be caused by the modulation of the signal due to the HMNS oscillation. Consequently, even if the efficiency of the mechanism that we propose results in a significantly smaller relative modulation, it is potentially observable.

An apparent concern would be that, given the expected frequencies of a few kHz, there would not be enough photon counts in the small time bins needed to resolve the period of an HMNS oscillation. However, as Lewin et al. (1988) pointed out, when the background is weak compared with the source, then the confidence level in terms of sigmas at which a feature corresponding to a signal with a fractional variation $a_{\rm osc}$ (due to an oscillation) will be detected can be estimated by

$$n_\sigma = \frac{1}{2} I a_{\rm osc}^2 \sqrt{\frac{\Delta T}{\Delta f}}, \tag{3}$$

where I is the source count rate, ΔT is the total observing time, and Δf is the frequency width of the peak in the Fourier spectrum.[7] Therefore, SGRB data can be searched for the HMNS oscillations even if the number of counts per time resolution element is small. Using the values estimated with Equation (3), we find that an oscillation with a fractional variation $a_{\rm osc} = 0.25$ would be detectable at the 11σ level by BATSE and at 8σ by *Swift*. The proposed missions TAP and STROBE-X will be able to detect the signal at the 5σ and 26σ level, respectively. Oscillations in an event with a flux three times higher than the average estimate of Ghirlanda et al. (2009), which is compatible with GRB 120323A, would be detectable by *Fermi* at over 5σ with a stronger fractional variation of $a_{\rm osc} = 0.4$.

4. Final Remarks

We have presented a preliminary analysis of the detectability of HMNS oscillations as modulation of SGRB signal emitted in the electromagnetic counterpart of a binary NS merger, showing promising results. Archival data from gamma-ray detectors can be searched for these signals, as well as future data obtained in coincidence with GW detections. However, the analysis of existing and future data should be performed carefully, as the frequencies may drift as the HMNS spins down during its lifetime.

Our analysis assumes that the SGRB is emitted during the HMNS phase after the merger. Therefore, the presence of these frequencies in the signal will favor the HMNS scenario for SGRB emission, whereas their absence would support scenarios involving prompt collapse.

The detection of frequencies corresponding to HMNS oscillations will provide information about the hot EOS after the merger, which cannot be probed by tidal deformability effects on the GW signal during the inspiral (prior to the merger). Additionally, if an SGRB is detected in coincidence with a future GW detection, it could facilitate a GW search for the HMNS oscillations with a lower detection threshold.

The authors thank Simone Dichiara, Bernard Kelly, Amy Lien, Scott Noble, Luciano Rezzolla, Bernard Schutz, and Jeremy Schnittman for useful discussions and comments on a previous version of this manuscript, and David Radice for kindly providing the NR simulation data. M.C.M. was at the Kavli Institute for Theoretical Physics during the completion of this Letter and was therefore supported in part by the National Science Foundation under grant No. NSF PHY-1748958. This work was supported in part by the Munich Institute for Astro- and Particle Physics (MIAPP) of the DFG cluster of excellence "Origin and Structure of the Universe" and by the Brazilian National Council for Scientific and Technological Development (CNPq grant 303750/2017-0).

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[6] Here we have assumed that the burst was detected directly by STROBE-X. However, the large area field of view of the LAD is small ($\approx 1°$ collimated) and a direct detection would be unlikely. A more likely scenario would be a burst outside the field of view, in which case only a fraction of the photons would reach the detector, with an unknown reduction factor in the effective area of the detector.

[7] In cases when the background is comparable to the signal, the source count rate I in Equation (3) must be replaced with $I^2/(I + B)$, where B is the background count rate. However, it is common though not universal to have $I \gg B$ in SGRBs; see Hakkila et al. (2018) for example light curves.

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