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Observational evidence for extended emission to GW170817

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ABSTRACT

The recent LIGO event GW170817 is the merger of a double neutron star system with an associated short GRB170817A with 2.9 ± 0.3 s soft emission over 8–70 keV. This association has a Gaussian equivalent level of confidence of 5.1σ. The merger produced a hypermassive neutron star or stellar mass black hole with prompt or continuous energy output powering GRB170817A. Here, we report on a possible detection of extended emission (EE) in gravitational radiation *during* GRB170817A: a descending chirp with characteristic time-scale $\tau_s = 3.01 \pm 0.2$ s in a (H1,L1)-spectrogram up to 700 Hz with Gaussian equivalent level of confidence greater than 3.3σ based on causality alone following edge detection applied to (H1,L1)-spectrograms merged by frequency coincidences. Additional confidence derives from the strength of this EE. The observed frequencies below 1 kHz indicate a hypermassive magnetar rather than a black hole, spinning down by magnetic winds and interactions with dynamical mass ejecta.

Key words: gravitational waves – methods: data-analysis – stars: neutron – gamma-ray bursts: individual: GRB170817A.

1 INTRODUCTION

The LIGO–Virgo detection of GW170817 (Abbott et al. 2017a) followed by the *Fermi*-GBM and INTEGRAL identification GRB170817A (Connaughton 2017; Savchencko et al. 2017) for the first time establishes a merger as the progenitor of a GRB. GRB170817A is classified as a short gamma-ray burst (SGRB) at $T_{90} = 2.0 \pm 0.5$ s ($\leq$300 keV) (Goldstein et al. 2017) with relatively soft extended emission over $T_{90} = 2.9 \pm 0.3$ ($\leq$70 keV) (Pozanenko et al. 2018) whose isotropic equivalent energy is below that of typical SGRBs by about four orders of magnitude (Kasliwal et al. 2017).

The GW170817/GRB170817A association is significant for our understanding of the origin of heavy elements by the r-process (Kasen et al. 2017; Pian et al. 2017; Smartt et al. 2017) and it possibly provides new measurements of the Hubble parameter H_0, independent of any of the existing methods (Abbott et al. 2017; Guidorzi et al. 2017; Riess et al. 2018). Observing tens of neutron star mergers in the near future may resolve the H_0 tension problem (Freedman 2017), promising new insights on weak gravity at the de Sitter scale of acceleration in the Universe (van Putten 2017b).

While GW170817 establishes a double neutron star merger as the origin of GRB170817A, it leaves unidentified its central engine (Usov 1992): is GRB170817A powered by prompt *or* continuous energy output from a newly formed hypermassive neutron star *or* black hole (Usov 1992; Woosley 1993; Nakar 2007; Ruffini et al. 2016a,b; Nagataki 2018)? It is widely believed that gravitational-wave observations have the power to resolve these questions (Cutler & Thorne 2002).

GW170817 produced a clear signal over 40-300 Hz in the Hanford (H1) and Livingston (L1) detectors of LIGO by an energy output $E_{\rm GW} > 2.5$ per cent $M_\odot c^2$, where c is the velocity of light. This may be accompanied by gravitational-wave emission just prior and after final coalescence. For instance, high frequency emission is expected from tidal effects starting at $f_t \sim 600$ Hz in the run-up to final coalescence (Hinderer et al. 2009; Reed et al. 2009; Damour, Nagar & Villain 2012; Del Pozzo et al. 2013; Wade et al. 2014), possibly accompanied by dynamical mass ejections (Baiotti, Giacomazzo & Rezzolla 2008; Faber & Rasio 2012; Baiotti & Rezzolla 2017) and post-merger signals may derive from a rapidly spinning central engine powering GRB170817A. Some confidence in this outlook derives from high-resolution numerical simulations, showing the formation of hypermassive neutron star–disc systems soon after f_t. After some delay, this system may collapse to stellar mass black hole (Baiotti et al. 2008), as in core-collapse of massive stars, e.g. SN1987A (Burrows & Lattimer 1987; Brown, Bethe & Lee 2003).

However, rigorous identification of the central engine of GRB170817A defies electromagnetic observations, given significant uncertainties in circumburst environment, viewing angle, and the unusual spectral-energy properties of this event (Abbott et al.

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2017b; Pozanenko et al. 2018). GW170817A may have formed a long-lived hypermassive neutron star, similar to the high temperature proto-neutron star in SN1987A inferred from neutrino energies in excess of 10 MeV. Its ∼10 s light curve is commonly attributed to slow neutrino diffusion in matter at supranuclear densities (Brown et al. 2003). But this emission might also derive from a high-density accretion disc around a newly formed black hole derived from fall back of a remnant stellar envelope giving $L_{\bar{\nu}_e} \quad 10^{51}\ \mathrm{erg\,s}^{-1}$ after the first few seconds (Blum & Kushnir 2016). Final remnants appear to be black holes, inferred from late-time X-ray emission (Ruan et al. 2018). If detected, an extended emission (EE) in gravitational-wave emission potentially provides a direct signature of a central engine, circumventing aforementioned uncertainties in electromagnetic and neutrino emission.

For GRB170817A, it appears opportune to search for emissions at energies $E_{\mathrm{gw}} \sim 1$ per cent$\mathrm{M}_\odot c^2$ up to about 1 kHz (Abbott et al. 2017d) given its fortuitous proximity of about 41 Mpc (Cantiello et al. 2018). By causality, EE in gravitational radiation is potentially meaningful to the central engine if it starts before GRB170817A, that is, during the 1.7 s gap between the time of coalescence $t_c = 1842.43$ s inferred from LIGO observations and the onset of GRB170817A detected by *Fermi*-GBM (Connaughton 2017) and INTEGRAL (Savchencko et al. 2017).

Here, we report on a search for broad-band extended gravitational-wave emission (BEGE) post-merger to GW170817A in a revisit of LIGO H1, L1, and V1 data from the LOSC (Vallisneri et al. 2014). Our model-independent search uses matched filtering over chirp-like templates that are time-symmetric, allowing detection of ascending and descending chirps with phase-coherence on time-scales of order of τ. We use $\tau = 0.5$ s, characteristic for extreme transients gradually exhausting a central energy reservoir over several seconds or more. Fig. 1 shows spectrograms up to 700Hz obtained by matched filtering over a dense bank of templates demonstrated previously in the identification of broad-band Kolmogorov spectra up to 1 kHz in light curves of long GRBs of the *BeppoSAX* catalogue (van Putten, Guidorzi & Frontera 2014).

When the template bank is sufficiently dense, sensitivity approaches that of ideal matched filtering (van Putten et al. 2014; van Putten 2017c), by linear amplification of signals to signal-to-noise ratios greater than unity before seeking coincidences or correlations between two or more detectors. For small signals, sensitivity of this approach appears to exceed that of power excess methods considered in existing model-independent searches for post-merger signals (Abbott et al. 2017).

Application of our *butterfly filter* to LIGO-Virgo data is made possible on a heterogeneous computing platform with multiple high-end *graphics processor units* (GPUs). Single-detector spectrograms are merged in searches for coincident features, which may be identified by edge detection (Canny 1986; MatLab 2018). Gaussian equivalent levels of confidence derive from causality following edge detection background analysis (Supplementary Information).

2 OBSERVATION AND INTERPRETATION

Zoomed in to the epoch about GW170817 (Fig. 2), the (H1,L1)-spectrogram shows the relatively loud merger signal of GW170817 with binary coalescence at $t_c = 1842.43$ (Abbott et al. 2017a) described by an *ascending chirp* in gravitational-wave frequency

$$f_m(t) = A(t_c - t)^{-\frac{3}{8}}(t < t_c) \tag{1}$$

identified up to 260 Hz, where $A \quad 138\ \mathrm{s}^{-5/8}$ Hz is representative of the chirp mass $\quad = c\,(15/768F(e))^{\frac{3}{5}}\,(\pi A)^{-\frac{8}{5}}$ $1.1382F(e)^{-\frac{3}{5}}\mathrm{M}_\odot$, including $F(e)$ accounting for ellipticity $e \quad 0$ (Peters & Mathews 1963; Abbott et al. 2017a). The gravitational-wave luminosity during the merger satisfies $L_{\mathrm{GW}} = (32/5)\,(\quad)^{\frac{10}{3}}\,L_0$, where $\quad = \pi f$ and $L_0 = c^5/G$, where G is Newton's constant. In the observed track up to 260 Hz, L_{GW} $1.35 \times 10^{50}\mathrm{erg\,s}^{-1} \quad 7.5 \times 10^{-5}\mathrm{M}_\odot c^2\,\mathrm{s}^{-1}$, i.e. $4 \times 10^{-10}L_0$, which is relatively gentle compared to $10^{-5}L_0$ of GW150914 at similar frequency.

Fig. 2 shows a continuation of GW170817 with a long-duration *descending chirp during* GRB170817A. It can be fitted by an exponential track (Supplementary Information)

$$f_p(t) = (f_s - f_0)e^{-(t-t_s)/\tau_s} + f_0(t > t_s) \tag{2}$$

with $\tau_s = 3.01 \pm 0.2$ s, $t_s = 1843.1$ s, $f_s = 650$ Hz, and $f_0 = 98$ Hz. Crucially, $t_s - t_c = 0.67$ s shows the descending chirp to start in the 1.7 s gap between GW170817 and GRB170817A, satisfying the aforementioned causality condition. A Gaussian equivalent level of confidence greater than 3.3σ obtains for significance to the central engine of GRB170817A based on causality over 1952 s of LIGO data. Improved estimates obtain upon including the statistical significance of the strength of the signal (Supplementary Information).

The estimated initial frequency $f_c = 774$ Hz at the time of coalescence inferred from (2) is below the orbital frequency at which the stars approach the *Inner Most Stable Circular Orbit* (ISCO) of the system as a whole, i.e. ∼1100 Hz at ∼16 km according to the Kerr metric (Kerr 1963; Bardeen, Press & Teukolsky 1972; Shapiro & Teukolsky 1983). At this point, a binary system of two equal mass neutron stars would have a rotational energy $E_{\mathrm{rot}} = 4.56$ per cent $\mathrm{M}_\odot c^2$ and a dimensionless specific angular momentum $\hat{a} = 0.72 < 1$. While this allows prompt collapse to an $\sim 3\,\mathrm{M}_\odot$ Kerr black hole (Kerr 1963) any gravitational-radiation from remaining debris orbiting about the ISCO would be above 2 kHz. Instead, the <1kHz descending chirp in Fig. 2 points to radiation of $E_{\mathrm{GW}} \quad 0.2$ per cent $\mathrm{M}_\odot c^2$ from a long-lived rapidly rotating hypermassive neutron star or magnetar with a dimensionless quadrupole moment of 0.2 per cent$(R/16\,\mathrm{km})^5$, where R is the radius of the star, induced by dynamical and secular instabilities (Owen et al. 1998; Kokkotas 2008; Corsi & Mészáros 2009) that may include magnetic fields (Cutler 2002; Abbott et al. 2017d).

Magnetar spin down indicated by the descending chirp may include magnetic interactions with surrounding matter from dynamical mass ejections from the preceding merger, in addition to gravitational radiation losses alone. These ejecta are commonly found in aforementioned numerical simulations. The interactions may result from magnetic coupling (Gosh, Pethick & Lamb 1977; Gosh & Lamb 1978, 1979) and/or tidal stresses (Hotokezaka et al. 2013) that may include magnetic outflows from open field lines (Lovelace, Romanova & Bisnovatyi-Kogan 1995; Parfrey, Spitkovksy & Beloborodov 2016) and gravitational-wave emission from quadrupole moments in orbiting debris.

While the descending chirp identifies the central energy reservoir of GRB170817A to be a rotating hypermassive neutron star or magnetar, its connection to GRB170817A remains uncertain. Perhaps the relatively soft second gamma-ray pulse of GRB170817A (Pozanenko et al. 2018) derives from outflows from debris orbiting the star, while the short-hard pulse derives from an initial outflow from the star at birth. More likely, the complex spectral evolution of GRB170817A derives from shock break-out (Kasliwal et al. 2017; Gottlieb 2018), producing a short-hard pulse followed by softer

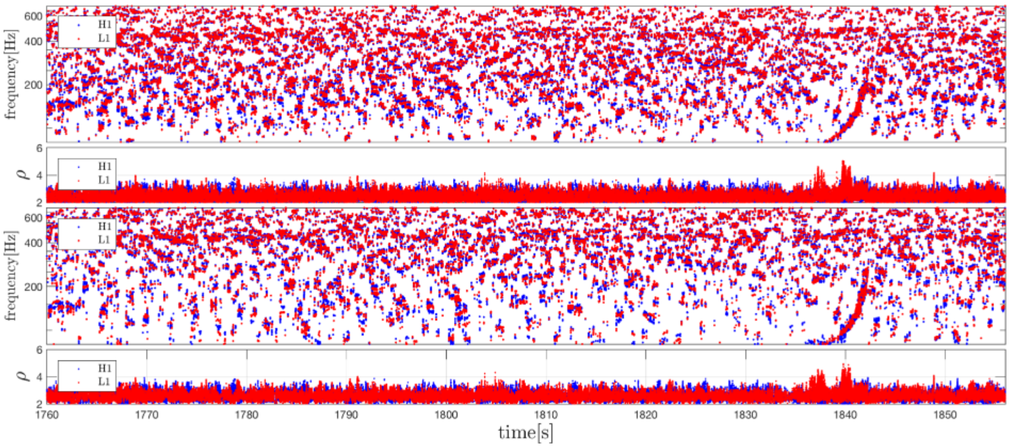

Figure 1. (H1,L1)-spectrograms covering GW170817/GRB170817A by coincidences in frequency ($\Delta f = |f_1 - f_2| < 10$ Hz, upper panels) and amplitude ($\rho_1\rho_2 > 6$, lower panels) of single detector spectrograms of H1 and L1 produced by butterfly filtering. A post-merger feature is apparent in the (H1,L1)-spectrogram merged by frequency more so than when merged by amplitude. Excess amplitudes during GW170817 are primarily due gravitational radiation below 100Hz.

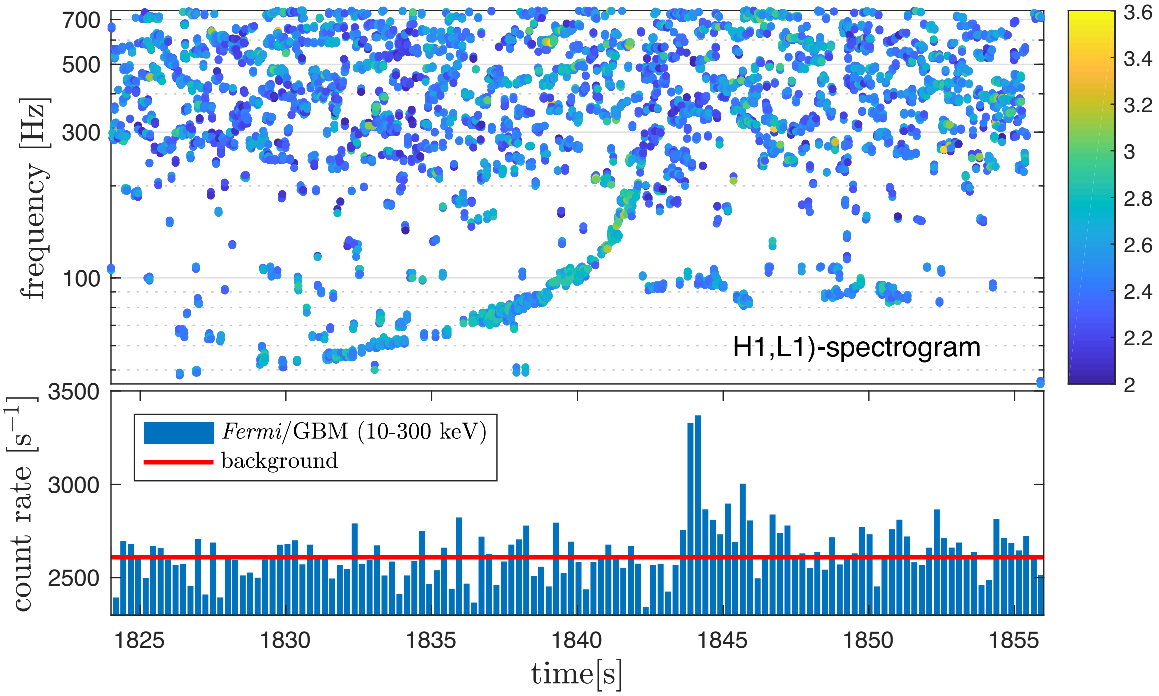

Figure 2. Ascending–descending chirp in the (H1,L1)-spectrogram produced by the double neutron star merger GW170817 concurrent with GRB170817A (Goldstein et al. 2017) past coalescence ($t_c = 1842.43$ s). Minor accompanying features around 100 Hz (1840-1852 s) are conceivably due to dynamical mass ejecta. Colour coding (blue-to-yellow) is proportional to amplitude defined by butterfly output ρ of time-symmetric chirp-like template correlations to data.

emission of relatively longer duration as the shock becomes more spherical as it propagates downstream.

3 CONCLUSIONS

We present observational evidence for a descending chirp for the first five seconds post-merger to GW170817 (Fig. 2). By frequency, it potentially indicates a magnetar as the central engine of GRB170817A, well below the minimum of 2 kHz emission from high density matter about the ISCO of a 3 $M_\odot$ black hole. The ultimate fate of the magnetar is uncertain, whether it survives as a pulsar with a spin frequency of 49 Hz or collapses to a black hole at a later stage. The physical mechanism by which the magnetar is protected against prompt collapse is not well understood, but lifetimes of 10 s such as observed here have been anticipated for proto-magnetars (Ravi & Lasky 2014). Our observation of an extended lifetime appears particularly reasonable in light of the recent LIGO determination of a relatively low total mass of $2.73^{+0.04}_{-0.01} M_\odot$ of the progenitor binary (Abbott et al. 2018) that is just 20 per cent above the neutron star mass of $2.27^{+0.17}_{-0.15} M_\odot$ in PSR J2215+5135 (Linares, Shahbaz & Casares 2018) and on par with the supermassive PSR J1748-2021B (Freire et al. 2008; Özel & Freire 2016).

Future observations promise to significantly improve on these initial observations, and to determine to what extend GRB170817A is representative for canonical SGRBs.

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SUPPORTING INFORMATION

Supplementary data are available at *MNRASL* online on Figs 1–2, quantifying statistical significance (4.2σ) by the statistically independent attributes of timing (3.3σ, Eq. A15) and amplitude (2.2σ, Eq. A.16).

Supplement GW170817EE_Suppl.pdf

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