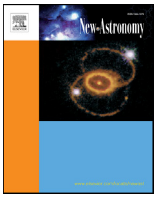
New Astronomy 42 (2016) 24–28

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast



Proposed searches for candidate sources of gravitational waves in a nearby core-collapse supernova survey

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HIGHLIGHTS

- A fraction of CC-SNe is expected to produce long gravitational wave bursts.
- CC-SNe are competitive with binary mergers if this fraction exceeds a mere 1%.
- The most nearby CC-SNe provide triggers of interest to LIGO-Virgo and KAGRA.
- Proposed is a robotic survey of nearby galaxies most prone to producing CC-SNe.

ARTICLE INFO

Article history:
Received 19 May 2015
Revised 18 June 2015
Accepted 19 June 2015
Available online 25 June 2015

Communicated by E.P.J. van de Heuvel

Keywords:
Core-collapse supernovae
Surveys
Gravitational waves

ABSTRACT

Gravitational wave bursts in the formation of neutron stars and black holes in energetic core-collapse supernovae (CC-SNe) are of potential interest to LIGO-Virgo and KAGRA. Events nearby are readily discovered using moderately sized telescopes. CC-SNe are competitive with mergers of neutron stars and black holes, if the fraction producing an energetic output in gravitational waves exceeds about 1%. This opportunity motivates the design of a novel Sejong University Core-CollapsE Supernova Survey (SUCCESS), to provide triggers for follow-up searches for gravitational waves. It is based on the 76 cm Sejong university telescope (SUT) for weekly monitoring of nearby star-forming galaxies, i.e., M51, M81-M82 and blue dwarf galaxies from the unified nearby galaxy catalog with an expected yield of a few hundred per year. Optical light curves will be resolved for the true time-of-onset for probes of gravitational waves by broadband time-sliced matched filtering.

1. Introduction

Broadly, supernovae appear with two different explosion mechanisms: core-collapse of massive stars and thermonuclear explosions.

Observationally, core-collapse events are classified as Type Ib, Type Ic or Type II (Filippenko, 1997). Type Ib events have no absorption lines of H, Si, but do show evidence of He. Their progenitors are believed to have ejected most of their hydrogen envelopes prior to the explosion, e.g., in Wolf–Rayet stars (WN). Type Ic events have no absorption lines of H, Si or He. Their progenitors may be Wolf-Rayet stars (WC) having lost both hydrogen and helium envelopes. Type Ib/c events may preferentially occur with close binary stellar companions, that strip the outer progenitor envelopes (Smartt, 2009; Yoon et al., 2010). Supernovae of Type II shows H absorption lines and those of Type II-P have plateau light curves, lasting up to about 100 d. Their progenitors are most likely massive red supergiants. Type II-L supernovae with no plateau show light curves dropping off beyond a peak. Their progenitors are believed to have already lost a large fraction of the hydrogen envelope prior to the event. Since Type II SNe are envelope retaining and Type Ib/c are envelope-stripped, the following Nomoto–Iwamoto–Suzuki sequence is suggestive (Nomoto et al., 1995; Turatto, 2003; van Putten, 2005)

$$\mathrm{IIP} \rightarrow \mathrm{IIL} \rightarrow \mathrm{IIb} \rightarrow \mathrm{Ib} \rightarrow \mathrm{Ic} \tag{1}$$

in order of decreasing H-mass envelope from about 10 $M_\odot$ down to $10^{-2}\,M_\odot$ (Elmhamdi et al., 2006). Lastly, Type Ia supernovae represent the thermonuclear explosion of white dwarfs. They may originate from mergers of two white dwarfs following in-spiral by gravitational radiation (Iben and Tutukov, 1984; Webbink, 1984). A spectroscopic study based on the sloan digital sky survey (SDSS; York et al., 2000) identified 15 double white dwarf systems out of 4,000 white dwarfs, that implies a double white dwarf merger rate of about once every century in the Milky Way. This event rate agrees with the

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http://dx.doi.org/10.1016/j.newast.2015.06.007
1384-1076/

observed rate in our neighborhood (Badenes and Maoz, 2012) and "ever green" theoretical predictions (Yungelson, 1994). A white dwarf merger may explain, for instance, the supernova remnant SNR 0509–67.5 (Warren and Hughes, 2010) given the absence of a remnant companion (Schaefer and Pagnotta, 2012).

Core-collapse supernovae (CC-SNe) and cosmological gamma-ray bursts (GRBs) represent the most extreme transient events in the Universe, wherein Type Ib/c supernovae are progenitors of the latter (GRBs; e.g. Galama et al., 1998; Bloom et al., 1999; Podsiadlowski, 2013). The origin of the most energetic long GRBs is probably found in extreme relativistic energy sources operating on the Schwarzschild radius of a compact stellar mass object (e.g. Fryer et al., 2014). As such, they are conceivably powerful sources of gravitational waves. Since Type Ib/c supernovae are more numerous than their offspring in GRBs by about two orders of magnitude, the much more broad class of energetic CC-SNe provide targets of opportunity for searches for gravitational wave bursts by advanced gravitational wave detectors. By the extreme relativistic nature of gamma-ray bursts, some of these should harbor relativistic inner engines with an associated output in gravitational wave emission, whether or not producing a "successful" or "failed" GRB. Specifically, this outlook can be probed using broadband gravitational wave detection methods.

We begin with a brief overview of the observational status of long GRBs and their potential as powerful gravitational-wave transients, closely following the association to their progenitor Type Ib/c supernovae (Section 2). This outlook points to our design of a dedicated automated survey of the latter, given that they are far more numerous than long GRBs (corrected for beaming; Section 3), focused on events in the most nearby galaxies (Section 4). Section 5 gives an outline of the survey built on the 76 cm Sejong university telescope applied to, e.g., the unified nearby galaxy catalogue (UNGC; Karachentsev et al. (2013); Kaisin and Karachentsev (2013)). Owned and operated by Sejong University, SUT can be fully dedicated to the proposed survey limited only by weather conditions. We conclude with a summary and outlook on follow-up probes by gravitational wave detectors Section 6.

2. Overview of GRB phenomenology

GRBs were serendipitously discovered in 1967 by the monitoring satellites Vela and publicly released in 1973 by Klebesadel et al. (1973). GRBs are flashes of gamma rays associated with extremely energetic explosions that have been observed in distant galaxies. Bursts can last from ten milliseconds to several minutes. Long duration GRBs are believed to arise from a narrow beam of intense radiation (Frail et al., 2001). The majority of GRBs originate in the core-collapse of probably rotating massive stars in binaries, probably forming a neutron star, quark star, or black hole.

Based on durations in the burst and transient source experiment (BATSE) catalog, GRBs are divided into two groups, short-duration GRBs (SGRBs) with an average duration of 0.3 s and long-duration GRBs (LGRBs) with a median duration of around 20 s (Kouveliotou et al., 1993). Durations of less than about 2 s define SGRBs, probably originating in the merger of two neutron stars or a neutron star and a companion black hole (e.g. Phinney, 1991; Belczynski et al., 2008; van Putten et al., 2014a). Most events (70%) have a duration greater than 2 s and are classified as LGRBs. LGRBs are probably connected with the death of massive stars.

More recently, ultra-long GRBs having a time profile lasting more than 10 ks have been recognized as an additional class of GRBs, that may result from the collapse of a blue supergiant star or the tidal disruption of, e.g., a white dwarf around a black hole in the intermediate mass range of less than $10^5 M_\odot$ (Levan et al., 2014). The tidal disruption event GRB 110328A had a gamma-ray duration of about 2 days (Bloom et al., 2011), much longer than even ultra-long GRBs, and was detected in X-rays for many months. There is an ongoing debate as to whether the explosion was the result of stellar collapse or a tidal disruption event accompanied by a relativistic jet (Campana et al., 2011; Thöne et al., 2011). Soft gamma-ray repeaters are a seperate class of GRBs. Of galactic origin (Hurley, 2009), they tend to have a softer spectrum than classical GRBs (i.e., SGRBs and LGRBs) and appear to be associated with repeating, non-destructive events occurring on magnetic neutron stars known as magnetars.

The non-thermal spectra of the prompt emission of classical short and long GRBs (Band et al., 1993) point to ultra-relativistic outflows from compact inner engines harboring neutron stars or stellar mass black holes (e.g. Piran, 2005; Piran and Sari, 1998). First evidence for the GRB-supernova association was found in GRB980425/SN1998bw (Galama et al., 1998) and GRB030329/SN2003dh (Hjorth, 2003; Stanek, 2003). More generally, it can be seen by supernova features in re-brightening bumps as optical transients appearing in a number of long duration GRB afterglow emissions, by photometry (Galama et al., 2000) and, rigorously, by spectroscopy (Della Valle et al., 2003; Levan et al., 2005). The aspherical explosion of core-collapse supernovae probably derives from jets within powered by rapidly rotating neutron stars or black holes (Bisnovatyi-Kogan, 1970; MacFadyen and Woosley, 1999; van Putten, 2015).

By their association to compact objects - neutron stars or black holes - GRBs are widely anticipated to be powerful sources of gravitational radiation of interest to LIGO-Virgo and KAGRA (Corsi, 2012)). Specifically, non-axisymmetric rapidly rotating high density matter on the scale of the Schwarzschild radius of a central engine will be luminous in gravitational waves, e.g., in deformations of the surface of a neutron star or accretion disks around neutron stars or black holes. In 2002–2010, surveys for gravitational wave in the local universe were conducted by the laser interferometer gravitational-wave observatory (LIGO) and the European detector Virgo at a sensitivity distance of about 8 Mpc for binary neutron star-neutron star coalescence (Abadie et al., 2012). The main LIGO-Virgo and KAGRA sources of gravitational radiation are stellar mass compact binaries of the BH-BH, BH-NS, and NS-NS variety, CC-SNe, relativistic pulsars, oscillations of neutron stars (w-modes, r-modes, etc.), and stochastic sources (astrophysical and cosmological), see, e.g., Cutler and Thorne (2002) for a comprehensive overview. Given the null-result for the 2002–2010 observations, the gravitational wave sky remains hitherto unexplored, and it becomes of interest to consider the potential significance of CC-SNe given their relatively large event rate compared to mergers.

Extreme core-collapse scenarios leading to long GRBs are believed to represent the formation of stellar-mass black holes with an accretion disk or a highly-magnetized neutron star. Though uncertain, in both cases GW emission is expected, whose spectra and amount of radiation should be quite different in bandwidth and luminosity. Simulations of non-extreme cases of core-collapse supernovae producing neutron stars identified numerous potential GW burst emission channels (e.g. Ott, 2009). For the extreme stellar collapse conditions necessary to power a long duration GRB, novel emission channels have been considered associated with non-axisymmetric accretion flows onto black holes. Gravitational wave emission may be particularly powerful from matter about the innermost stable circular orbit (ISCO) powered by a central rapidly rotating black hole (van Putten, 2001). Their emission signal features a characteristic negative chirp in gravitational waves (van Putten et al., 2011b), distinct from the positive chirp produced in mergers as precursors to SGRBs (e.g. Phinney, 1991). A detection of gravitational waves associated with a long or short GRB is almost surely to provide direct identification of their inner engine (Cutler and Thorne, 2002). By their large event rate, energetic CC-SNe such as those of Type Ib/c will be competitive to mergers as candidate sources for LIGO-Virgo and KAGRA, whenever the fraction that successfully produces a gravitation burst exceeds about 1%.