The astrophysical science case for a decihertz gravitational-wave detector

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Abstract
We discuss the astrophysical science case for a decihertz gravitational-wave mission. We focus on unique opportunities for scientific discovery in this frequency range, including probes of type IA supernova progenitors, mergers in the presence of third bodies, intermediate mass black holes, seeds of massive black holes, improved sky localization, and tracking the population of merging compact binaries.

Keywords: gravitational-wave astrophysics, double white dwarfs, binary black holes

(Some figures may appear in colour only in the online journal)

1. Introduction

The recent detections of gravitational waves from merging binary black holes (Abbott et al 2016c) and binary neutron stars (Abbott et al 2017b) by the ground-based advanced LIGO (Aasi et al 2015) and Virgo (Acernese et al 2015) gravitational-wave detectors have stimulated interest in the full spectrum of gravitational-wave astronomy. Pulsar timing arrays are actively searching for gravitational waves in the nanohertz frequency band (Hobbs et al 2010, Verbiest et al 2016); a space-born LISA detector, sensitive in the millihertz band, is scheduled to be launched in the 2030s (Bender et al 1998, Amaro-Seoane et al 2017); and there are ongoing investigations into a future ground-based detector with improved low-frequency sensitivity reaching down to a few hertz, e.g. the Einstein telescope (Punturo et al 2010) and the cosmic explorer (Abbott et al 2017a). In this paper, we make the astrophysical case for a detector that would slot in between the LISA band and the Einstein telescope band, with peak sensitivity around 1 decihertz. This science case partly overlaps the cases already made for terrestrial detectors such as the Einstein telescope (Sathyaprakash et al 2012) and the MANGO detector (Harms et al 2013), as well as the proposed space missions DECIGO (Seto et al 2001, Ando et al 2010), ALIA and BBO (Phinney et al 2004, Crowder and Cornish 2005).
Here, we focus on the key science questions that may not be answered by either ground-based detectors sensitive above 1 Hz or millihertz space detectors, but could be addressed by decihertz instruments. We do not consider any specific instruments with associated noise spectra, although a broad range of recent proposals, from the TianQin space detector (Luo et al 2016) to atom interferometers (e.g. Graham et al 2013, 2017), could be sensitive in the band of interest. Instead, we focus on the main scientific challenges, and where appropriate discuss the sensitivities necessary to address these.

In particular, we highlight the promise of decihertz detectors to pinpoint the progenitors of type IA supernovae; search for dynamical signatures of the merger environment; explore intermediate mass black holes; localize compact binaries on the sky; explore the evolutionary history of stellar-mass compact-object binaries; and investigate the light seeds of massive black holes.

2. Type IA supernova progenitors

Do type IA supernovae come from the merger of two white dwarfs (the double degenerate channel) or from accretion onto a white dwarf from a main sequence or giant companion (the single degenerate channel) (e.g. Livio 2000, Han and Podsiadlowski 2004, Nielsen et al 2014)? This has been a topic of active debate with differing interpretations of the observational evidence in the literature (e.g. Gilfanov and Bogdán 2010, Hayden et al 2010, Mennekens et al 2010, Nugent et al 2011, González Hernández et al 2012, Howell 2011).

Gravitational-wave observations in the decihertz band could help resolve this question. Joint observations of GW emission and a supernova would indicate the double degenerate channel, while the absence of a gravitational-wave signal preceding a nearby type IA would indicate the single degenerate channel, as the stellar companion would have been disrupted at lower frequencies.

The gravitational-wave frequency for a circular binary with total mass \( M \) and orbital separation \( a \) is given by

\[
f_{GW} \approx 0.1 \text{ Hz} \left( \frac{M}{2M_\odot} \right)^{1/2} \left( \frac{a}{0.02R_\odot} \right)^{-3/2}. \tag{1}
\]

Depending on the companion mass, a double WD binary could survive until it reaches an orbital radius \( \sim 0.02R_\odot \) (see Dan et al 2011) for somewhat lower numerical estimates of the maximum gravitational-wave frequency). However, if the white dwarf’s companion is a main sequence star or a giant, the companion would be disrupted at much larger separations. Therefore, the presence of gravitational waves in the decihertz band would be a tell-tale sign for the double degenerate channel. (An explosion could be delayed by as much as \( 10^5 \) yr following the merger in the double-degenerate channel (Yoon et al 2007), in which case one would not expect a correlation between gravitational waves and a type IA supernova even if this channel is operating, but more recent work suggests that prompt post-merger explosions are likely (Pakmor et al 2012). Meanwhile, if the double-degenerate channel proceeds via head-on white dwarf collisions in triples (Kushnir et al 2013), there may not be a strong associated gravitational-wave signature (but see Toonen et al 2017).)

The rate of type IA supernovae is roughly 1 per century per Milky Way equivalent galaxy (Cappellaro et al 1999), while the space density of such galaxies is \( \sim 0.01 \) Mpc\(^{-3}\) (Kopparapu et al 2008). Therefore, to have a realistic chance of observing at least one type IA supernova per year, \( \sim 10^4 \) Mpc\(^3\) must be surveyed—roughly the volume out to the Virgo cluster. (In fact, this would yield a slightly greater rate because of the local over-density of galaxies (Kopparapu et al 2008)).
et al 2008), which would compensate for the possible non-detection of some nearby supernovae due to unfavourable sky locations, etc). Hence the gravitational-wave detector should also be sensitive out to \( \sim 20 \) Mpc for such signals on average—or out to \( \sim 50 \) Mpc for optimally located and oriented events (Finn 1996).

The amplitude of the frequency-domain gravitational-wave signal from a binary inspiral viewed face on is (Ajith et al 2008)

\[
|\tilde{h}(f)| = \sqrt{\frac{5}{24\pi^{4/3}}} M_c^{5/6} f^{-7/6} r^{-1},
\]

where the chirp mass \( M_c = 2^{-1.2} M \) for an equal-mass binary, \( r \) is the distance to the source, and dimensionless units \( G = c = 1 \) are assumed. The signal-to-noise ratio \( \rho \) for a detector with one-sided noise power spectral density \( S_n(f) \) is given by

\[
\rho^2 = 4 \int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)} df.
\]

We can now use these expressions to check whether a given noise spectrum would be sufficient to allow a double white dwarf binary with \( M_c \sim M_\odot \) to be detected out to \( r_{\text{max}} \sim 50 \) Mpc at optimal location and orientation. For example, assuming that the detector has a flat noise power spectral density \( S_n(f) = S \) between \( f_{\text{min}} \) and \( f_{\text{max}} \) and limited sensitivity elsewhere, the sensitivity requirement on \( S \) for a detection threshold \( \rho_{\text{min}} \) is

\[
S \lesssim 2 \times 10^{-42} \text{ Hz}^{-1} \left[ \left( \frac{f_{\text{min}}}{0.1 \text{ Hz}} \right)^{-4/3} - \left( \frac{f_{\text{max}}}{0.1 \text{ Hz}} \right)^{-4/3} \right] \left( \frac{M_c}{M_\odot} \right)^{5/3} \left( \frac{r_{\text{max}}}{50 \text{ Mpc}} \right)^{-2} \left( \frac{\rho_{\text{min}}}{8} \right)^{-2}.
\]

In order to quantify the science requirements on a decihertz detector, we consider a detector with optimal sensitivity between \( f_{\text{min}} = 0.1 \) Hz and \( f_{\text{max}} = 0.2 \) Hz, and place constraints on the maximum noise power spectral in that frequency band. We take this band as illustrative of the science enabled by such detectors; however, many of the science cases discussed here would still be achievable with peak sensitivity shifted in frequency, and, of course, broadband detectors would generally improve the science reach. We find that \( S \lesssim 10^{-42} \text{ Hz}^{-1} \) if the detection threshold is \( \rho_{\text{min}} \geq 8 \); this threshold assumes coherent matched filtering and stationary, Gaussian noise.

Equation (4) can be inverted to obtain the distance reach \( r_{\text{max}} \) as a function of \( S \). This reach is shown in figure 1. At cosmological scales, \( r_{\text{max}} \) in equations (4) and (6) becomes the luminosity distance, while the masses are the redshifted masses, \( M \rightarrow M (1 + z) \), where \( z \) is the redshift.

The timescale until a gravitationally-wave driven merger for a circular binary with a current gravitational-wave frequency \( f_{\text{GW}} \) is (Peters 1964)

\[
\tau_{\text{GW}} \approx 10 \text{ yr} \left( \frac{M_c}{M_\odot} \right)^{-5/3} \left( \frac{f_{\text{GW}}}{0.1 \text{ Hz}} \right)^{8/3}.
\]

Thus, a binary with a chirp mass of \( 1M_\odot \) would need almost 10 yr to evolve from a gravitational-wave frequency of 0.1 Hz to a gravitational-wave frequency of 0.2 Hz.

At even lower frequencies, when the evolutionary timescale \( \tau_{\text{GW}} \) is much longer than the observing duration \( T_{\text{obs}} \), so that the signal can be considered as roughly monochromatic at frequency \( f_{\text{GW}} \), the sensitivity requirement given in equation (4) is modified to
\[ S \lesssim 5 \times 10^{-43} \text{ Hz}^{-1} \left( \frac{M_\odot}{M_{\text{bin}}} \right)^{10/3} \left( \frac{f_{GW}}{0.05 \text{ Hz}} \right)^{4/3} \left( \frac{T_{\text{obs}}}{5 \text{ yr}} \right) \left( \frac{r_{\text{max}}}{50 \text{ Mpc}} \right)^{-2} \left( \rho_{\text{min}} \right)^{-2}. \] (6)

3. Mergers in the presence of third bodies

Low-frequency, long-duration observations are potentially sensitive to astrophysical perturbations to gravitational-wave driven binary evolution, such as Doppler shifting of the gravitational-wave signature due to the orbital motion of the inspiraling binary relative to a tertiary companion in the system (e.g. Seto (2008)). The Doppler shift is given by

\[ \delta f \approx 10^{-5} \text{ Hz} \left( \frac{f_{GW}}{0.1 \text{ Hz}} \right) \left( \frac{M_\odot}{M_{\text{bin}}} \right)^{-0.5} \left( \frac{a}{\text{AU}} \right)^{-0.5}, \] (7)

where \( M_{\text{bin}} \) is the mass of the merging compact binary emitting gravitational waves at frequency \( f_{GW} \) and \( m \ll M_{\text{bin}} \) is the mass of the tertiary companion at a separation \( a \) from the binary. Fluctuations \( \delta f \gtrsim 1/(\rho T_{\text{obs}}) \) should be detectable as long as the observation time \( T_{\text{obs}} \) is larger than the outer orbital period \( 2\pi a^{3/2}(GM)^{-1/2} \). The readily inferred presence of a third companion could indicate the importance of the Lidov–Kozai mechanism (Lidov 1962, Kozai 1962) in driving binaries to merger.

Conversely, if the binary is merging within the sphere of influence of a massive black hole—the merger of a stellar-mass binary may be assisted by the accretion disk in an active galactic nucleus (Bartos et al. 2016, Stone et al. 2017)—the orbital period around the massive black hole is typically much longer than the observation duration. A constant Doppler shift is
degenerate with a cosmological redshift or a change in the mass of the binary. However, the orbital acceleration of the binary around the massive black hole of mass $M_{\text{MBH}} \gg M_{\text{bin}}$ will be detectable when the accumulated acceleration-induced phase shift to the gravitational-wave signal exceeds $\sim 1/\rho$,

$$\frac{1}{2} \frac{GM_{\text{MBH}}}{a^2} \frac{f_{\text{GW}}}{T_{\text{obs}}/c} \gtrsim \frac{1}{\rho},$$

i.e. when

$$f_{\text{GW}} \gtrsim 0.02 \, \text{Hz} \left( \frac{M_{\text{MBH}}}{10^6 \, M_\odot} \right)^{-1} \left( \frac{a}{\text{pc}} \right)^2 \left( \frac{T_{\text{obs}}}{5 \, \text{yr}} \right)^{-2} \left( \frac{\rho}{8} \right)^{-1}$$

for a suitable binary orientation relative to the line of sight. Thus, decihertz gravitational waves from a double neutron star or double white dwarf inspiraling within a massive black hole’s sphere of influence will carry the signature of its environment. On the other hand, the merger timescale from $f_{\text{GW}} = 0.1$ Hz for a binary black hole is much shorter than 5 yr (see equation (5)). Therefore, to detect the imprint of the massive black hole on the gravitational waves from a merging stellar-mass black hole binary, either the detector sensitivity would need to extend down to $\sim 0.01$ Hz, or the merger would need to happen within $\sim 1000$ AU of the massive black hole.

The density in the center of the most massive core-collapsed globular clusters is comparable to the mass concentration within the sphere of influence of a massive black hole. Therefore, gravitational-wave signatures of decihertz binaries in globular clusters may also carry an imprint of their environment; in fact, it may challenging to determine whether a massive black hole or a globular cluster is responsible for the acceleration for binaries at 1 pc.

## 4. Intermediate mass black holes

A decihertz mission could be the optimal tool for searching for $\sim 1000 M_\odot$ intermediate mass black holes (IMBHs). Black holes in this mass range are notoriously challenging to convincingly find. Their small sphere of influence means that only a handful of nearby objects show unambiguous dynamical impact of the IMBH (e.g. Miller and Colbert (2004), Kızıltan et al 2017, Freire et al 2017). Meanwhile, possible ultra-luminous x-ray binaries could be interpreted as either IMBHs (e.g. Pasham et al 2014) or super-Eddington accretors (Bachetti et al 2014). Gravitational-wave observations of either inspirals of stellar-mass compact objects into IMBHs, or mergers of two IMBHs, could thus provide the first convincing evidence of their existence.

The gravitational-wave frequency from an innermost stable circular orbit around a black hole of mass $M$ is

$$f_{\text{ISCO}} \approx 4.3 \, \text{Hz} \left( \frac{M}{1000 \, M_\odot} \right)^{-1},$$

placing such massive black holes outside the range of ground-based detectors insensitive below a few Hz (Gair et al 2011, Belczynski et al 2014), but into the range of decihertz detectors.

If black holes in this mass range naturally reside in globular clusters, intermediate-mass ratio inspirals should be generic (e.g. Haster et al 2016a), and the mass of the black hole could be confirmed through the associated gravitational-wave signature (Haster et al 2016b). The local space density of globular clusters is a few per Mpc$^3$, and an upper limit on the merger
rate can be estimated by assuming that the intermediate mass black hole builds up its mass through minor mergers over the $\sim 10^{10}$ yr cluster lifetime (Mandel et al 2008). Thus, if a few percent of all globular clusters host a $\sim 1000M_\odot$ black hole, an intermediate mass ratio coalescence of such an IMBH and a $\sim 1000M_\odot$ companion may occur at a rate of up to one merger per Gpc$^3$ per year. The detector described above would be sensitive to these coalescences at Gpc-scale distances, and could therefore realistically detect such inspirals and confirm the existence of intermediate mass black holes in this mass range. Such confirmation could also come from mergers of IMBH binaries (Amaro-Seoane and Freitag 2006).

Observations of coalescences involving IMBHs would enable exploration of globular cluster dynamics. These coalescences could also provide electromagnetic counterparts if the inspiraling compact object is a white dwarf rather than a neutron star or black hole (Sesana et al 2008). An inspiral of a white dwarf into an intermediate mass black hole in the $10^4M_\odot$ range could be detectable to $z \gtrsim 0.5$ for a detector with noise power spectral density $S \sim 10^{-43}$ Hz$^{-1}$ between 0.1 and 0.2 Hz; Sesana et al (2008) argue that at least a few such inspirals should happen in this range per year. Such white dwarf tidal disruptions have been proposed as a possible source of a recently observed population of faint x-ray transients (Jonker et al 2013, Glennie et al 2015, Bauer et al 2017).

5. Massive black hole formation

Decihertz detectors could look for gravitational waves from light seeds of today’s massive black holes (MBHs). MBHs inhabit the center of essentially all massive galaxies in the nearby Universe (Kormendy and Richstone 1995, Magorrian et al 1998), and their masses correlate with the properties of the galaxy host, pointing toward MBH-host co-evolution (see Kormendy and Ho (2013), and references therein). This implies that following galaxy mergers, MBHs form MBH binaries (Begelman et al 1980), which are expected to be loud sources of GWs. The merger rate of such binaries strongly depends on the early occupation fraction of the first MBH ‘seeds’ and on their masses (Volonteri et al 2003, Sesana et al 2011). In particular, different scenarios for forming the first BH seeds have been proposed in the literature (see Volonteri (2010), for a review). Seeds forming from the direct collapse of protogalactic disks in the mass range $10^4M_\odot$–$10^5M_\odot$ are ideal targets for the LISA mission. On the other hand, the decihertz band is the ideal window to catch potentially lower $\approx 100M_\odot$ seeds, left behind by the first generation of stars (Pop III). At $z \sim 10$, the observed merger frequency of those binaries is approximately 1 Hz, according to equation (10); therefore, some of the seeds, merging later / at lower redshifts, may even be observable with the Einstein telescope (Sesana et al 2009, Gair et al 2009).

Decihertz detectors should be sensitive to such binaries, making them invaluable probes of structure formation. As shown in figure 2, a detector with noise power spectral density $10^{-42}$ Hz$^{-1}$ between 0.1 and 0.2 Hz would be sensitive to mergers of two optimally oriented $2000M_\odot$ seeds out to $z \sim 20$, whereas a spectral density of $10^{-44}$ Hz$^{-1}$ in the same frequency range would be sufficient to cover the relevant mass range down to seeds of $100M_\odot$, thus directly probing the very first seed BH mergers.

6. Sky localization

A double neutron star emitting at a gravitational-wave frequency of 0.1 Hz will only merge in several years according to equation (5). A decihertz detector will thus complete several orbits around the Sun while the source is in band. For sky localization purposes, such a detector effectively behaves as a set of detectors with a baseline of order the size of the orbit.
The timing accuracy for a signal that evolves through the full sensitive frequency band of the detector during the observing time scales inversely with the detector bandwidth $f_{\text{bandwidth}}$ and inversely with the signal-to-noise ratio (Fairhurst 2009, Grover et al. 2014); for a decihertz detector with an assumed $f_{\text{bandwidth}} \sim 0.1$ Hz, $\sim$1 s timing can be expected, though very broadband detectors could further improve timing accuracy. For a slowly evolving or nearly monochromatic signal at frequency $f$, the timing accuracy scales as $1/\rho f$, as the phasing (and hence the timing of a particular phase of the wave) can be determined to a fraction $1/\rho$ of the wave cycle. The sky localization accuracy can then be estimated as the timing accuracy divided by the light travel time across the detector baseline:

$$\sigma_{\theta} \sim \frac{0.0025}{f} \frac{0.1 \text{ Hz AU}}{\rho \text{ baseline}},$$

(11)

where $f_{\text{bandwidth}}$ should be used in place of $f$ for signal that evolves out of the band on the timescale of observations. This approximation is equivalent to considering the impact of Doppler shifting of the signal by the motion of the detector.

For a multi-year source, a baseline of 2 AU or 1000 light seconds yields a sky localization accuracy of $\sim$0.001 radians or a few arcminutes (Takahashi and Nakamura 2003, Graham and Jung 2017)—though the accuracy of the localization will depend on the location of the source relative to the detector’s orbital plane. This would make it possible to accurately point smaller field-of-view, sensitive telescopes for electromagnetic follow-up. It would even allow for host galaxy identification for nearby, $r \lesssim 500$ Mpc, sources, allowing host environments to be explored even in the absence of a confirmed counterpart.

A heavy stellar-mass black hole binary with $\sim 30M_\odot$ components will merge in about a week from a gravitational-wave frequency of 0.1 Hz. Its baseline will be much shorter—only 10 light seconds—and the arc is almost a straight line, with minimal perpendicular displacement to provide orthogonal directional sensitivity; therefore, accurate localization and host identification would remain challenging.

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**Figure 2.** Signal-to-noise ratio contour plots for optimally oriented equal mass black hole binaries with total mass indicated on the abscissa merging at a redshift indicated on the ordinate. The two plots depict the capabilities of detectors with $S = 10^{-42}$ Hz$^{-1}$ (left panel) and $S = 10^{-44}$ Hz$^{-1}$ (right panel) between $f_{\text{min}} = 0.1$ Hz and $f_{\text{max}} = 0.2$ Hz.
7. Evolutionary history of compact object binaries

Together with other gravitational-wave instruments—space-born LISA, and ground-based advanced LIGO (Aasi et al. 2015) and Virgo (Acernese et al. 2015) detectors and their successors such as the proposed Einstein telescope (Punturo et al. 2010)—a decihertz detector can ensure that the full frequency spectrum is covered for stellar-mass binary black holes and neutron stars.

Multi-frequency observations can improve the accuracy with which source parameters can be measured. Tracking an individual source across a range of frequencies could yield both information that is most readily accessible at higher frequencies and at lower ones. For example, tidal effects for neutron stars or the total mass and final spin from the ringdown of a post-merger black hole would be measured with high-frequency observations. On the other hand, as discussed above, sky localization can be significantly enhanced with lower-frequency observations.

Of particular interest are measurements of spin magnitude and misalignment angle distributions, which could carry information about formation scenarios (e.g. Vitale et al. 2017, Stevenson et al. 2017, Zevin et al. 2017, Farr et al. 2017) and the mass ratios, which would help constrain masses and test for the existence of a mass gap between neutron stars and black holes (Belczynski et al. 2012, Mandel et al. 2015, Littenberg et al. 2015). The mass ratio and spin-orbit coupling come into the waveform at higher orders in the orbital velocity (Poisson and Will 1995) and may therefore be better constrained at higher frequencies. However, the presence of $\sim 10^5$ (heavy stellar-mass black hole binaries) to $\sim 10^7$ (double neutron stars) cycles in the decihertz band could, in fact, allow for more precise constraints. Specific detector performance would need to be considered for a quantitative assessment of parameter inference with decihertz observations.

In addition to individual sources, it may be possible to track changes in source populations as they evolve between different frequency bands. For example, residual eccentricity, which would strongly indicate dynamical formation (e.g. Abbott et al. 2016a), may only be observable at lower frequencies, as binaries will circularize through gravitational-wave emission by the time they reach the frequency band of classical ground-based detectors. On the other hand, very eccentric sources at low frequencies could be more difficult to detect (Chen and Amaro-Seoane 2017), and their emergence at higher frequencies would indicate high birth eccentricity.

8. Stochastic background

The stochastic background from a superposition of gravitational waves emitted by multiple individually unresolvable binary inspirals in this frequency band should be a known power law in frequency (Abbott et al. 2016b). The amplitude of this power law will be sensitive to mergers at a higher redshift than the individually resolvable source population, but will still add only a single number to the information gained from that population. However, observations at these and higher frequencies may make it possible to remove the astrophysical background. This would make a potential gravitational-wave background of cosmological original (e.g. Mandic et al. 2012, Lasky et al. 2016) accessible to observation (Callister et al. 2016, Regimbau et al. 2017).

9. Discussion

We have outlined the exciting astrophysical potential of a decihertz detector. We estimated the sensitivity required to achieve several key science goals that can best be addressed in this
frequency band, including investigating the progenitors of type IA supernovae, measuring the dynamics in the merger environment, searching for intermediate-mass black holes and light seeds of today’s massive black holes, and exploring the evolutionary history of compact object binaries.

As always, exploring a new spectral band opens the potential for unexpected discoveries. For instance, predicted but elusive gravitational waves from cosmic string cusps may be detectable in this band.

Decihertz observations may also enable more precise tests of general relativity, or at least tests in a different regime of velocities and tidal field strengths (e.g. Chamberlain and Yunes (2017)). For example, the mass quadrupole moment of the compact bodies could be measured and compared with the value predicted from mass and spin in the Kerr metric (Brown et al 2007, Rodriguez et al 2012).

Our estimates will need to be followed up for specific proposed detector noise power spectra in order to quantitatively evaluate the prospects discussed above. In particular, rigorous estimates of parameter inference accuracy combined with realistic astrophysical models will be required to appraise the resolving power of intermediate-frequency GW detectors.

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