PHYSICS

Special Topic: Gravitational Wave Astronomy

Science prospects for space-borne gravitational-wave missions

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The detection of the gravitational-wave (GW) signals GW150914, GW151226 together with the transient candidate LVT151012 by Advanced LIGO (aLIGO) marked a new era of GW astronomy [1]. While ground-based GW detectors have opened a new window to explore the universe, joint observations with ground-based and space-borne GW missions, such as those with heliocentric orbits [2] or geocentric orbits [3], can greatly enhance our exploration capability. Furthermore, sources under extreme conditions involving massive black holes can only be thoroughly investigated by space-borne gravitational-wave missions.

In contrast with ground-based GW detectors, space-borne missions can have a longer armlength and a much more stable low-frequency noise background; thus they are sensitive to a lower-frequency band. Possible future missions under active investigation [2,3] are most sensitive in the frequency band of about 0.1 mHz–1 Hz. A wide range of astronomical sources lurk in this frequency range. This makes space-borne GW detectors most exciting instruments in the GW window, tuned to unravel a wide spectrum of puzzles in astronomy as well as in physics [2,4–6].

Within our Galaxy, there are hundreds of millions of binary systems composed of compact objects like white dwarfs, neutron stars and/or black holes. GW detectors operating in space can discover such systems in their thousands, while traditional observational methods can only reveal the tip of the iceberg. The strength and density of GW signals from these systems are deeply intertwined with the very late stage of binary evolution, which contains great uncertainty due to the complicated physical process involved.

By observing and analyzing these GW signals, space-borne GW missions are ideal probes to explore the late-stage stellar binary evolution. Models of the common envelope phase, the formation channel of type Ia supernovae (SNe Ia) and the role of tidal interaction as well as stability during mass transfer can all be studied with unprecedented precision. Furthermore, the directional sensitivity of GW detectors can provide extra information on Galactic structure, by distinguishing contributions of GW signals from halo and from disk [7].

In the nearby universe, compact binary coalescence events have been directly detected by advanced LIGO. The unexpectedly high masses of the GW150914 black holes imply that such systems can also produce GW signals detectable by space-borne missions, which suggests the promising field of multi-band GW astronomy [1].

GW signals from the compact binary merger evolve in frequency from the space band (∼0.01 Hz) to the ground band (∼100 Hz) within around 10 years, and the frequency increases faster and faster as the binary approaches merger [8]. Thus space-borne GW detectors sensitive to higher space-band frequencies, like TianQin [3], are expected to make a more significant contribution to this field of multi-band GW astronomy (Fig. 1). Such an early-warning scenario makes possible a deeper and more comprehensive observation of an event that spends time in the detection band of both space-based and ground-based detectors.

GW observation at the low-frequency inspiral stage can determine the chirp mass to high accuracy; thus the coalescence time as well as frequency can be precisely predicted long before the final merger. The GW detector network composed of multiple satellites is constantly rotating, changing antenna pattern, thus inducing a periodic modulation to the GW signal. Moreover, the mass center of the detectors follows an annual orbit around the Sun, providing an extra modulation due to Doppler shift. Both modulations encode the sky location of the source; thus, careful analysis can alert other observational facilities with a

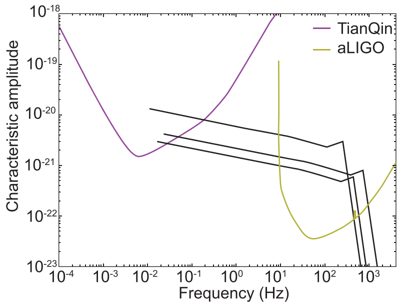

Figure 1. Characteristic amplitude of the detected GW signals GW150914, GW151226 and candidate LVT151012 (from top to bottom). Ten years before merger, such binary black hole systems lie in the TianQin band. After that, the systems would evolve and eventually merge in the sensitive band of ground-based detectors.

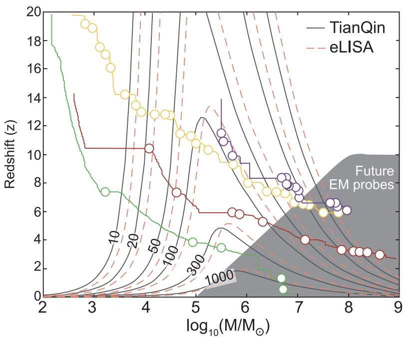

Figure 2. Signal-to-noise ratio (SNR) contour for space-borne GW missions, using TianQin [3] and eLISA [2] as examples. Assuming no spin and an equal-mass MBH system and average over sky, the detector is most sensitive to systems with 10^4–$10^7 M_\odot$, which largely overlap with various MBH growth predictions, indicated by four different lines (modified and reprinted with permission from [2]). For details we refer interested readers to [2].

timing accuracy as good as 0.1 s. A multi-messenger observation (and even non-observation) for such a compact binary coalescence event can greatly enrich our knowledge of extreme events, such as gamma-ray bursts and fast radio bursts. In the meantime, detecting GW signals from different bands will also allow a thorough examination of our understanding of gravity, put extremely stringent constraints on the graviton mass and the speed of propagation of GWs, as well as test the black hole no-hair theorem [4,8,9].

Throughout the whole universe, massive black holes (MBHs) in the center of galaxies play an important role in galaxy evolution. The hierarchical formation theory of galaxy growth predicts frequent mergers of MBH binaries within the range of 10^3–$10^7 M_\odot$, whose frequency at merger lies firmly inside the sensitive band of space-borne GW missions. (Figure 2 demonstrates how the MBH evolve throughout cosmic time, cutting across the sensitive band of space detectors.) This mass range overlaps with that of intermediate-mass black holes (IMBHs) of 10^2–$10^5 M_\odot$, which is largely unexplored by electromagnetic astronomy observations. Thus, by studying these sources, one can decode the formation history of galaxies, and deeply understand the growth of both the central MBH and the galaxy itself. Meanwhile, MBHs also provide an ideal laboratory for testing theories of gravity. Compact objects like stellar-mass black holes orbiting around MBHs act like test particles responding to the gravitational field of the MBH. Thus the GW signal from such extreme mass-ratio inspirals (EMRIs) will provide an extremely accurate measurement of spacetime near the MBH. Thus the test of the Kerr metric could be pushed to the extreme, with tiny deviations from general relativity easily spotted and thoroughly examined [2,4,6].

Besides these expected GW sources, the opening of every new window in astronomy has always brought surprises. Beyond the anticipated mechanisms, there are unknown physical processes that might emit GW signals, and any new discovery might lead the road to the realm of new physics.

In conclusion, space-borne GW missions can observe a wide range of astronomical sources, including compact binaries orbiting in our own galaxy and coalescing in the nearby universe, and physical processes involving MBHs throughout cosmos history. The operation of space-borne GW missions brings a promising future of multi-band GW astronomy as well as multi-messenger astronomy, and it will greatly enrich our understanding of the universe that we are immersed in.

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