Space-Based Gravitational Wave Observations in the Mid-Band Frequency Region

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

☒Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☐Galaxy Evolution ☒Multi-Messenger Astronomy and Astrophysics

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Abstract:

The opportunity exists to scientifically explore the intermediate Gravitation Wave (GW) frequency detection band, a region that is in between those accessible by LISA and LIGO. This GW region has unexplored and exciting sources. A GW mission capable of accessing this part of the GW band will complement and enhance the scientific capabilities of both LIGO and LISA. This frequency band could be accessible by a low-cost space-based interferometric detector. This is because in this frequency region the dominant acceleration noise sources on the spacecraft are significantly smaller than their magnitudes at lower frequencies. This results in a major simplification of the science package onboard each spacecraft as the Gravitational Reference Sensor (GRS) and its drag-free control system are no longer required. Only precision laser interferometry is needed. A GW mission probing the mid-frequency band could be flown by the late-2020 as it would rely only on laser interferometry technology derived from that already flown successfully onboard the GRACE Follow-On mission.

Scientific Background: Gravitational Wave Astronomy

The first LIGO [1] detection of a gravitational wave (GW) signal from the merger of two medium mass Binary Black Holes (BBH) [2], followed by the observation of mergers from further BBHs [3-5] and one binary neutron star [6], mark the beginning of GW astronomy. Because of seismic noise, the lower part (below 10 Hz) of the GW spectrum will be accessible only to space-based detectors such as the European-led LISA mission [7], which is expected to fly in the year 2034.

The opportunity exists to fly in the late-2020s a low cost GW mission covering the GW frequency region that is not accessible by LIGO and LISA. With 3 spacecraft in a geocentric orbit and separated by about 10^5 km a GW mission can achieve good sensitivity over a frequency region between LISA and LIGO. Such a GW frequency band is characterized by the presence of thousands of galactic white-dwarf binary systems, a very large ensemble of coalescing BBHs similar to those observed by LIGO (Fig. 1) [8], Intermediate Mass Ratio Inspiral binaries (IMRIs) [9], and signals emitted by unexpected astrophysical sources. Intermediate mass BBH of the type observed by LIGO, in particular, are characterized by frequencies sweeping upwards from the mHz to the kHz bands because of radiation reaction driving their dynamic evolution. The GW mission we envision will detect thousands of such signals with good signal-to-noise ratio (SNR) and enhance the LIGO science by measuring with high precision the parameters characterizing such signals (source direction, chirp parameter, time to coalescence, etc.) weeks before they will enter the LIGO band [10]. This valuable information will enhance LIGO's ability to detect these signals and facilitate their study of the merger and ring-down phases not accessible by space-based detectors [8]. This synergism between space- and ground-based detectors could be further enhanced if our proposed interferometer's and LISA's operations would overlap [11].

A mid-band GW mission will be able to address key questions about the origin and evolution of the Universe, in line with NASA's scientific long-term goals. By observing and studying gravitational waves emitted by mid-mass black-holes strongly interacting with Dark Matter objects we will be able to infer properties of this large yet unknown constituent of the Universe. The ability of studying the anticipated large population of intermediate-mass binary black-holes of the type detected by LIGO in the kHz band will allow us to understand the formation mechanism of these highly relativistic objects and provide key information about them to enhance LIGO's scientific objectives. Observations of coalescing binary black-holes with masses of $10^2 - 10^4$ M_0 will allow us to test the no-hair theorem in a frequency region inaccessible by LIGO and LISA.

Mission Concept

The GW mission we envision entails three satellites in a high geocentric orbit. They are arranged as an equilateral configuration of side-length of about 100,000 km, with precision laser interferometry to measure the inter-spacecraft laser frequency fluctuations. Because of the large radius of the satellite orbits the optical paths of the interferometer will be well above the Earth atmosphere, resulting in a negligible phase noise contribution. The key difference between our proposed interferometer and LISA, however, is that a Gravitational Reference Sensor is not needed and it results in a significantly simpler payload. The existence of the interferometry package successfully flown onboard GRACE-FO [12] means that much of the required technology has been developed and only modest further technology development is required to enable this mission. The target frequency band between LISA and LIGO also means significantly relaxed thermal stability requirements over that for LISA and resulting flexibility in spacecraft choice.

The onboard science instrument for the mission we have analyzed is significantly simpler than that to be flown onboard LISA because it will operate in the frequency region that is two orders of magnitude higher than that accessible by LISA. Solar radiation pressure fluctuations on the spacecraft will be smaller by more than four orders of magnitude than those experienced by LISA. For this reason our GW mission does not need an onboard GRS system. Along the same lines of reasoning, the satellites do not require the same thermal stability as those of LISA, resulting in a much simpler spacecraft design. In summary, our mission concept will not need to fly on each of its three spacecraft any proof-mass; the complexity of the onboard system architecture will be significantly reduced.

A geosynchronous gravitational wave detector concept was conceived in 2010 and studied at JPL from the beginning of 2013 until the end of 2016 [13, 14, 15]. The scientific objectives of our GW mission are compelling and the enthusiasm for a mid-band detector has increased rapidly due to the LIGO observations and realization that our mid-band detector could have seen the LIGO black hole binary's about a month before it entered into the LIGO band [11].

We anticipate the overall mission cost to be significantly lower than a flagship-class mission, fitting into the Probe, or possibly Explorer cost guidelines because of cost reductions of satellites and launching vehicle, together with a simplified onboard instrument design. Coincidentally, researchers in France [16] have independently studied a 3 CubeSat mission concept similar to ours, without a GRS system and in a geosynchronous trajectory. Their design also includes large cost reductions coming indeed from eliminating the GRS and its associated drag-free control. Further simplifications are enabled by operating at higher frequency, where noise from solar radiation pressure fluctuation and temperature-driven effects are significantly lower.

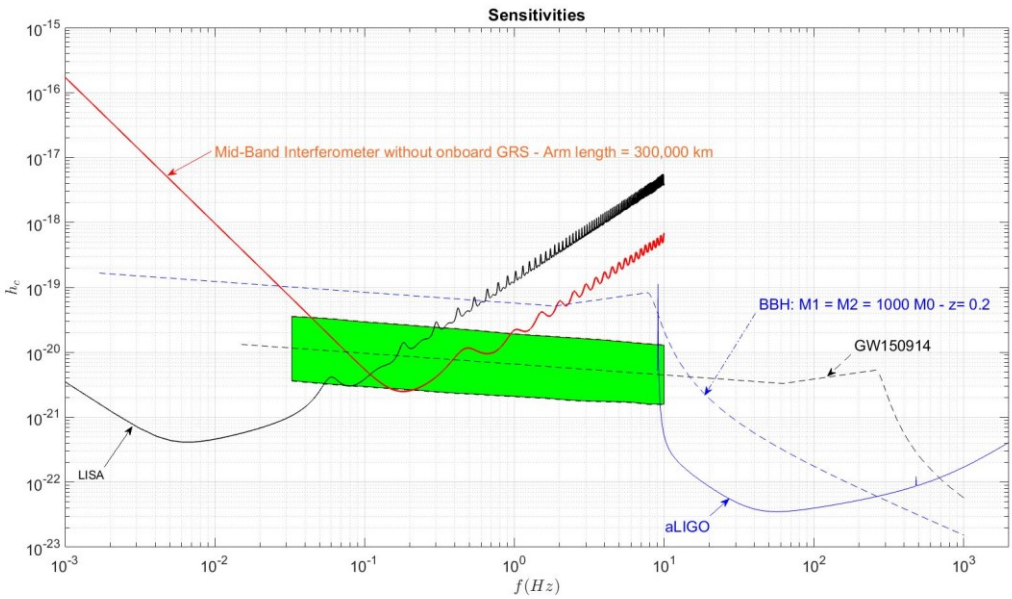

Figure 1. The sensitivity of LIGO (blue line) together with the anticipated sensitivities of LISA (black line) and our currently studied GW mission concept (red line). Our mission will rely on flight-heritage hardware for interferometry and will not need a drag-free system. Included is the predicted ensemble of medium-mass BBH (bright-green band), GW150914 (the first GW signal detected by LIGO) and a 10^3 M_0 BBH at z=0.2. Our mission will also detect BBH with masses up to 10^4 M_0, Galactic white-dwarf white-dwarf binaries, and unanticipated sources radiating within its sensitivity band.

Furthermore, since the three satellite configuration will be affected by the same radiation pressure at geometrically related time-delays, its noise transfer function to the interferometric observables will fall-off in the lower part of the frequency band, further suppressing its magnitude. Working at higher frequencies also eliminates the need for extraordinary temperature-stable optics, allowing small light-weight optical fiber routing to replace LISA's complex massive optical bench and enabling the use of a conventional design for the telescopes. Rather than LISA's long-baseline Earth-trailing orbits, our interferometer's satellites will be in an orbit that can be reached with a single-launch Falcon 9 and without the need for satellites' propulsion modules. A comparison between the main characteristics of the LISA the mission and our current mission concept are summarized in the table below.

	LISA	Mid-Band Mission
Launch Date	2034	Late 2020's
	3 satellites + 6 laser links	3 satellites + 6 laser links
Orbit	Earth-trailing	Geocentric
Arm Length	2.5 M km	300,000 km
Launch Vehicle	Single-launch & S/C with propulsion modules	Falcon 9 & S/C *without* prop. modules
Telescope	30 cm	30 cm
Inertial Reference Sensor	LISA Pathfinder GRS and drag-free control – $a(f) = 3 \times 10^{-15}$ m/s^2 Hz$^{-1/2}$	*No* GRS & *No* drag-free control system
Laser Power	1 W	1 W
Strain Sensitivity	4.6×10^{-22} @ 10 mHz	2.5×10^{-21} @ 0.2 Hz
GW Sources	• Super-Massive BH Binaries • WD-WD binaries • Stellar-mass galactic binaries • Extreme-Mass-Ratio Binaries • Signals from Unexpected sources	• Stellar-mass galactic binaries • Intermediate Mass-Ratio Inpiral Binaries • BBH with masses 10 – 10^4 M_0 • Signals from Unexpected sources

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