Topical:

Lunar Gravitational-wave Detection

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Moon as a platform for GW detectors

Lunar gravitational-wave (GW) detection has been under consideration since Apollo 17 when the Lunar Surface Gravimeter developed under the coordination of Joseph Weber was deployed on the Moon with the goal to observe lunar surface vibrations generated by passing GWs [1]. The experiment did not run with its targeted performance, but even if it had, we know today that it would not have been sensitive enough to detect GW signals. Vibrations caused by GWs are expected to be several orders of magnitude weaker than what the instrument was designed to observe. The main motivation to bring such an experiment to the Moon was that with the extremely low level of seismicity observed with previously deployed Apollo seismometers [2] (see figure 1), Weber suspected that GW signals could be detected.

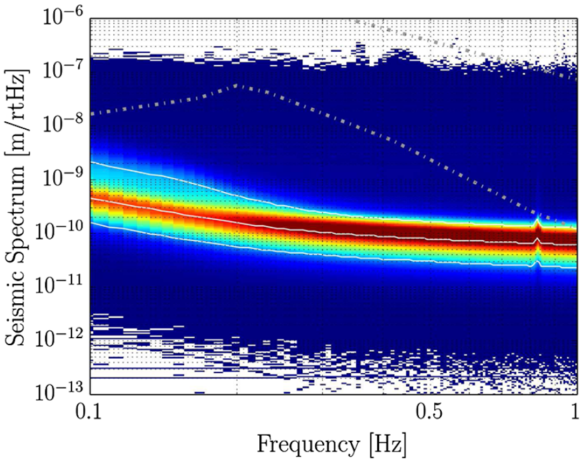

FIG. 1: Histogram of lunar seismic spectra observed by a seismometer deployed with Apollo 16. Moonquakes and meteoroid impacts cause larger disturbances (upper blue part of the histogram). A continuous seismic background was not revealed. The red mode in this plot was observed most of the time, and it corresponds to the instrument noise of the seismometer. A seismic background from meteoroid impacts is expected 3 orders of magnitude below the red mode. Minimal seismic levels on Earth are indicated by the lower dashed-dotted curve.

Next-generation terrestrial gravitational-wave (GW) detectors have been proposed including the Cosmic Explorer in the US [3] and the Einstein Telescope in Europe [4]. Construction of these research infrastructures is expected around 2035 with a targeted lifetime of at least 50 years. The space-borne detector LISA is an approved mission orbiting the Sun expected to be launched in the second half of the 2030s. It has a nominal lifetime of four years, but with potential to be extended by several years. We propose the Moon as a third platform for future GW detectors. The Moon's unique properties lead to unique opportunities for GW science. Specifically, the Moon offers the possibility to explore the decihertz GW regime that would bridge the frequency spectrum between space-borne observatories and terrestrial detectors.

The **Moon is the seismically quietest known place in our solar system** ideally suited for long-term installations of GW detectors. The Moon also **offers some of the lowest temperature environments in the solar system**, namely the so-called permanently shadowed regions (PSRs) near the lunar south and north poles, which have been and will be mapped accurately by several lunar orbiters, like NASA's LRO and other recent and imminent missions (like ISRO's Chandrayaan-2 and South Korea's KPLO, respectively). Some of these regions can have temperatures that lie continuously below 40 K and are therefore suitable for cryogenic instruments.

The creation of instruments sensitive to GWs is among the greatest technological challenges of modern physics. Current GW detectors are extremely complex systems, and it requires several years for a commissioning crew to understand their instrument sufficiently well to be able to bring it to the targeted performance. The complexity is to a large extent connected to a sophisticated isolation system that suppresses the influence of the environment on the detector. A low-noise environment as provided by the Moon promises crucial advantages over terrestrial sites.

An advantage of lunar GW detectors compared to space-borne detectors is that their lifetime has no known hard limit. Some of the Apollo seismic stations had been running for almost 8 years until the experiment was terminated. The first challenge of achieving a long lifetime is the power system, which is a problem to be solved for many other lunar scientific experiments and exploration missions. Nonetheless, the potential for nominal operation times of 10 years and longer would make it possible to create an extended lunar GW detector network with time, which would benefit the science, and it would also lay out a possible scenario for international collaboration with different space agencies contributing to the network.

Opportunities for breakthrough GW science

The interesting observation band for lunar GW detectors reaches from 1 mHz to 50 Hz. The low-frequency limit is set by the elastic properties of the Moon causing the resonance-frequency of its lowest-order vibrational mode to lie around 1 mHz. Below 1 mHz, we can expect that space-borne detectors like LISA will always have too great of an advantage. Instead, above 50 Hz, we can expect that terrestrial GW detectors will always be the superior technology, since isolation from the noisy terrestrial environment is not a major challenge at these frequencies.

The lunar observation band includes the decihertz

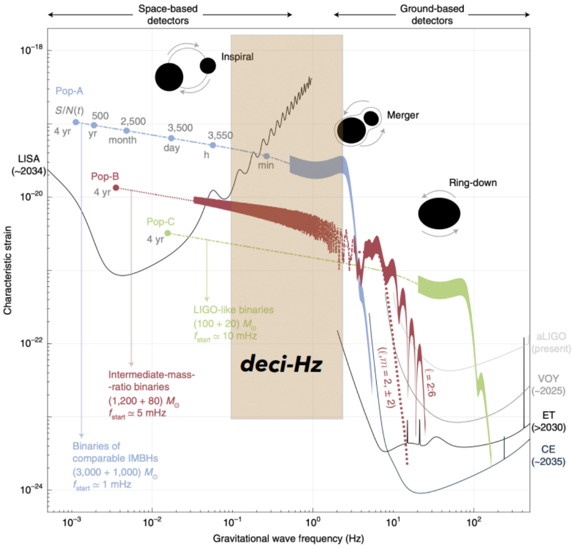

FIG. 2: Observations by LISA and terrestrial GW detectors will leave an uncovered band marked in orange. Signals in this band carry a lot of information and could be revealed by lunar GW detectors. Furthermore, rich synergies with future space-borne and ground-based detectors would be possible. Plot adapted from Jani et al [5].

frequencies 0.1 Hz – 1 Hz. It is a special band since neither the LISA mission nor the proposed future terrestrial detectors will cover it (see figure 2). In fact, one can argue that terrestrial GW detectors will never become a suitable technology for observations below a few Hz due to gravitational fluctuations produced by seismic and atmospheric fields. **A lunar GW detector could achieve first decihertz GW detections** with immense potential for breakthrough science.

Important features of lunar GW detection impacting the science outcome:

- Access to the decihertz band makes it possible to observe binary neutron stars months to years before their merger with accurate source-location estimates, which would enable deep investigations of the electromagnetic counterparts produced during the merger.
- Since the Moon has a shorter rotation period than the orbital period of LISA-type detectors, more precise locations of massive black-hole binaries could be obtained with lunar GW detectors by observing amplitude modulations of signals due to changing detector orientations.
- Lunar GW detectors can be long-lived experiments, which greatly facilitates the construction of a network of lunar detectors. Such a network would make it possible to carry out correlation measurements for stochastic GW searches [6], and do fundamental tests of general relativity [7].

The science case of lunar and decihertz detectors is reported elsewhere in great detail [5, 8–11]. Multiband observations from mHz to kHz involving terrestrial, space-borne and lunar GW detectors will increase the precision of source-parameter estimation. A few double white-dwarf mergers per year can be observed each year and shed light on a possible connection to Supernovae Type Ia. It would allow scientists to do deeper studies of these standard candles for measurements of the Hubble constant and the equation of state of dark energy. Lunar GW detectors would enable a cosmological survey of intermediate-mass black holes ($100 - 100,000\ M_\odot$) due to a superior detection horizon for these sources (see figure 3). Black holes in this mass range are key traces of the first generation of stars and seeds for super-massive black holes at the centers of galaxies.

Lunar GW detector concepts

Two methods have been proposed to detect GWs on the Moon. The first is to measure the elastic response of the Moon to GWs, the second is to build a detector with suspended test masses analogous to current LIGO and Virgo detectors. Exploiting the response of the Moon to GWs leads to simpler detector technologies since it is sufficient to observe surface vibrations of the Moon. However, such schemes will eventually be limited by a seismic background from meteoroid impacts and moonquakes. There are two strategies to overcome these limitations. Either one uses an array of seismic sensors to be able to partially cancel seismic disturbances from the data, or one uses suspended test masses and seismic isolation systems.

How much seismic noise can be suppressed by cancellation depends on the properties of the lunar seismic field and on how many sensors are deployed [12]. Optimization methods of such noise-reduction schemes are currently under development for the terrestrial GW detectors [13]. Instead, the construction of an interferometer with suspended test masses on the Moon is above all a question of feasibility. Based on current detector technologies, it would require a years-long presence of a team of trained astronauts on the Moon able to work in suitably controlled and protected operational conditions. NASA is foreseeing next-generation spacesuits capable of supporting future Artemis astronaut activities in PSRs up to 2 hours. Significant advances in robotic operations and drop of transportation cost from Earth to Moon might make this concept feasible and affordable in the future. These goals of human exploration, robotic advances and cost-effectiveness are common to several lunar programs, including: NASA's CLPS (Commercial Lunar Payload Services) and PRISM (Payload and Research Investigations on the Surface of the Moon); the international Artemis Accords; ESA's EL3 (European Large Logistics Lander); the Sino-Russian ILRS

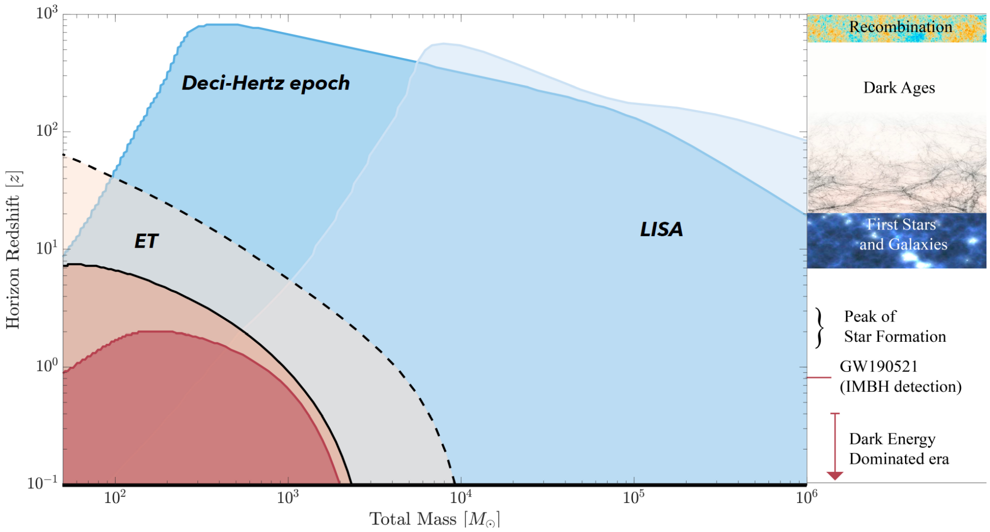

FIG. 3: Lunar GW detectors as decihertz concepts are sensitive to a broad range of black hole masses and astrophysical scenarios with a detection horizon that peaks for intermediate-mass binary black holes [5]. The horizon for decihertz epoch shown here represents a prospective reach for lunar GW detectors.

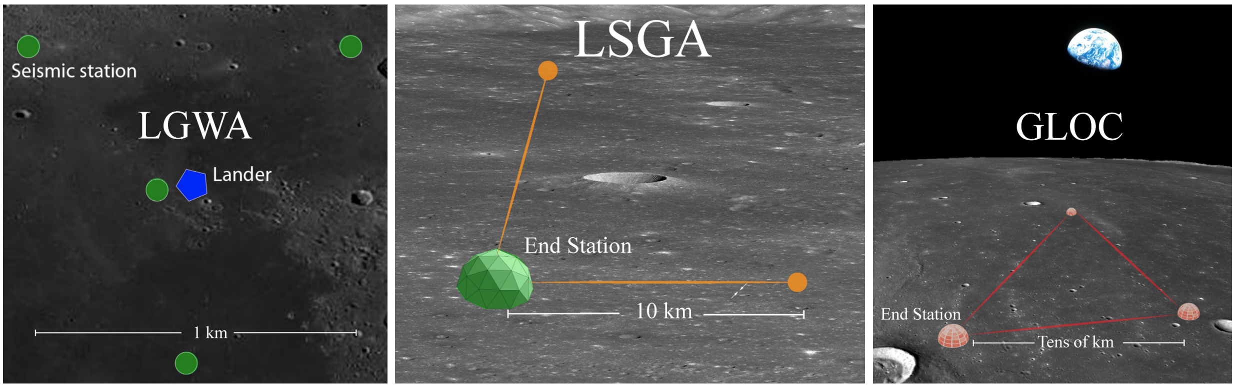

FIG. 4: (a) The LGWA concept consists of a kilometer-scale array of at least 4 cryogenic seismometers in a PSR of the lunar poles. The array makes it possible to suppress the noise of the seismic background in the GW data. (b) The LSGA concept is a long-baseline laser interferometer to measure seismic strains of the Moon produced by GWs. Seismic sensors can be deployed to reduce seismic disturbances in the data. (c) The GLOC concept is a long-baseline interferometer with suspended test masses and seismic isolation to measure GW strain similar to the ground-based detectors LIGO and Virgo.

(International Lunar Research Station). In the following, we summarize the three lunar GW detector concepts proposed in 2020 (see figure 4).

a. Lunar Gravitational-wave Antenna The Lunar Gravitational-wave Antenna (LGWA) was proposed in 2020 in response to ESA's call of ideas for science missions with the EL3 [10, 14]. It consists of an array of high-precision seismometers deployed in one of the PSRs, which exist at the lunar poles. The seismometers are built from superconductor materials and electronics, and they require operation at a few Kelvin, which must be provided by a low-vibration cryocooler [15]. Deployment and operation of the payload faces challenges similar to the Lunar Geophysical Network [16]. It is expected that a seismic background dominates ground vibrations above 0.1 Hz. The array serves to suppress contributions from a seismic background in the data making it possible to reveal weaker GW signals. The targeted GW observation band of LGWA is 1 mHz – few Hz.

b. Lunar Seismic and Gravitational Antenna The Lunar Seismic and Gravitational Antenna (LSGA) was proposed in 2020 in response to ESA's call of ideas for science missions with the EL3 [17]. It foresees the deployment of a long-baseline laser interferometer for measurements of lunar seismic strain produced by GWs in addition to 3-axis seismometers for calibration of data and mitigation of seismic signals [18]. Laser interferometry is well understood from current terrestrial

GW detectors LIGO and Virgo, and it has also been used for seismic strain measurements [19]. Furthermore, laser retroreflectors have been in use since the Apollo missions providing information on how the lunar environment affects their performance over time [20], and new retroreflector experiments have been proposed and will be flown to the Moon with two approved CLPS-PRISM mission opportunities by NASA and ESA between end 2023 and beginning 2024 (the latter with active retroreflector pointing and dust protection) [21]. The targeted GW observation band of LSGA is 1 mHz – few Hz.

c. Gravitational-wave Lunar Observatory for Cosmology The Gravitational-wave Lunar Observatory for Cosmology (GLOC) was proposed in 2020 [11]. It is based on the laser-interferometer concept with isolated test masses, which is also used in LIGO and Virgo and has led to the only GW detections so far [22, 23]. The primary target of GLOC is to push the low-frequency reach of this technology well beyond the limits of future terrestrial laser-interferometric GW detectors (below 3 Hz [4]). GLOC takes advantage of the natural vacuum above the lunar surface (two orders of magnitude better than in LIGO) to extend the interferometer length to tens of kilometers. The optics and test masses will be placed inside landers (or shielded domes) positioned at the vertices of a triangular setup (see Fig 4.c) GLOC, by design, will have its GW measurement isolated from lunar surface motion.

Lunar GW detection as part of a lunar exploration program

A comprehensive description of how the three detector concepts tie to lunar exploration must be given elsewhere (we refer to research campaign papers under preparation). Here, we outline some aspects of lunar GW detectors relevant to, and fully synergistic with, lunar exploration and lunar science.

a. Synergies with lunar geophysical missions All three lunar GW detector concepts can directly contribute to our understanding of the Moon. LGWA and LSGA are essentially high-precision seismic stations, and GLOC requires the implementation of sensitive accelerometers for detector isolation and control. As such, they would be able to provide unique contributions to a future lunar seismic network. The most important will be the recording of normal modes excited by the moonquakes, which are expected to have amplitudes $> 5 \cdot 10^{-13}\,(\mathrm{m/s^2})/\sqrt{\mathrm{Hz}}$ for shallow moonquakes with moment $> 10^{14}\,\mathrm{Nm}$ [24]. Moreover, it is conceivable that GWs can be used as probes to better understand the lunar interior structure by observing how the Moon responds to GWs. The key here is that GW signals can be modeled precisely (e.g., using knowledge of a GW signal from common observations with terrestrial GW detectors), which allows us to infer elastic properties of the Moon when observing surface vibrations caused by GWs. In fact, this scheme will be necessary to *calibrate* the GW response of the Moon.

With important infrastructure in place for a long-lived experiment including a power system, communication relay, etc, conditions are ideal for the deployment of other experiments connected to geophysical investigations. A **network of optical fibers** was proposed as part of LSGA, which would greatly help with studies of the lunar seismic field, its sources, and the shallow lunar internal structure. In addition, **next-generation laser retroreflectors** to be customized for inclusion in LSGA, have been developed also to be part of geophysical instrument packages (like for Apollo) and may further contribute to lunar science and to the test of general relativity in weak-field, slow-motion regime.

b. South pole exploration The lunar south pole is a prime target of future exploration missions as it might host ice and other resources inside the PSRs. Permanently shadowed regions are also proposed as deployment site for the cryogenic instruments of LGWA, and the thermal stability they provide is also expected to lead to an environment with reduced seismic perturbations (absence of thermally triggered ground motion). From that perspective, PSRs are ideal deployment locations also for LSGA and GLOC. However, powering of an experiment in a PSR for several years requires special power systems, as for example laser or microwave power beaming or a next-generation nuclear power system. It is a challenge that LGWA shares with other exploration missions of the south pole and other long-duration missions. Since the deployment of long-lived seismic stations in a PSR will remain a challenge, optical fibers (proposed to be part of LSGA) could be an alternative approach since they could be extended from a sunlit area into the PSR making solar panels a possible source of electric energy.

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