PROCEEDINGS OF SCIENCE

Space gravitational wave antenna DECIGO and B-DECIGO

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DECIGO is a future Japanese gravitational wave detector in space, designed to enhance gravitational wave astronomy. Operating within a frequency range of 0.1 Hz to 10 Hz, DECIGO plays a vital role in detecting gravitational wave signals from various sources, including primordial gravitational waves (PGWs). The pre-conceptual design of DECIGO features a cluster of three spacecraft, each equipped with lasers and floating mirrors, enabling precise measurements of gravitational waves. However, recent advancements in our understanding of the upper limit of PGWs have necessitated an update to DECIGO's design. The updated design aims to significantly improve DECIGO's sensitivity. Additionally, in preparation for DECIGO, a smaller version called B-DECIGO is planned for launch to test various technologies and achieve important scientific objectives. The ongoing development and updates in DECIGO's design demonstrate its potential to revolutionize gravitational wave astronomy and contribute to significant scientific discoveries.

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1. Introduction

The Deci-hertz Interferometer Gravitational Wave Observatory (DECIGO) [1] [2] is a future Japanese gravitational wave detector in space. DECIGO is expected to further enhance gravitational wave astronomy, which has been established through the first and subsequent detections of gravitational waves [3] [4] by the Laser Interferometer Gravitational-Wave Observatory (LIGO) [5] and the Virgo gravitational wave detector (Virgo) [6]. DECIGO is also expected to advance the scientific knowledge gained from the Laser Interferometer Space Antenna (LISA) [7] and ground-based detectors, such as LIGO, Virgo, and the Large-scale Cryogenic Gravitational Wave Telescope (KAGRA) [8] [9], as well as the planned future third-generation detectors, such as the Einstein Telescope (ET) [10] and Cosmic Explorer (CE) [11]. Prior to the realization of DECIGO, we intend to launch B-DECIGO [12] to demonstrate technologies for DECIGO and detect gravitational waves from various sources.

In this document, we will present the pre-conceptual design, target sensitivity, and intended scientific objectives of DECIGO in Chapter 2. We will then explain the need for updating the design of DECIGO and highlight related studies in Chapter 3. In Chapter 4, we will provide the roadmap for DECIGO and discuss B-DECIGO. We will also briefly mention SILVIA, which is a related technology demonstration mission. Finally, in Chapter 5, we will provide a summary.

2. Pre-conceptual design, target sensitivity, and intended science

DECIGO aims to detect gravitational waves in the frequency range between 0.1 Hz and 10 Hz. This frequency range lies just above the LISA frequency band and just below ground-based gravitational wave detectors, eenabling DECIGO to bridge the frequency gap between LISA and ground-based detectors. Consequently, DECIGO can fulfil a crucial role, particularly in detecting gravitational wave signals from inspiraling compact binaries, by acting as a follow-up to LISA and a precursor for ground-based detectors.

The pre-conceptual design and planned orbit of DECIGO are shown in Fig. 1. Each DECIGO cluster consists of three spacecraft positioned at the corners of an equilateral triangle with a distance of 1,000 km between them. Each spacecraft houses a laser and two floating mirrors, forming three dual-pass differential Fabry-Perot interferometers. The laser operates at a power of 10 W and a wavelength of 0.515μm. The mirrors have a radius of 0.5 m and a mass of 100 kg each. The arm cavity has a finesse of 10. The spacecraft's position is controlled by a drag-free system with the assistance of thrusters, ensuring that the mirrors remain in a free-floating state inside the spacecraft. These clusters will be placed in a heliocentric Earth-trail orbit. The separation of the three clusters optimizes the localization of sources. Additionally, two

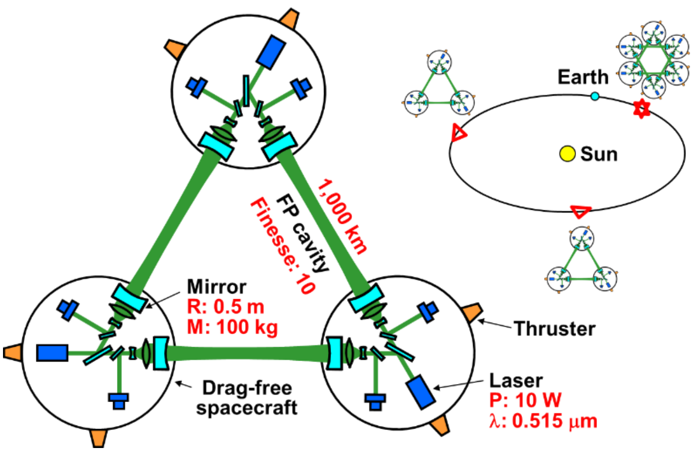

Fig.1. Pre-conceptual design (left) and planned orbit (right) of DECIGO.

clusters are positioned at the same location to enhance the sensitivity to stochastic gravitational waves, such as primordial gravitational waves (PGWs).

The target sensitivity of DECIGO is illustrated in Fig. 2, along with the anticipated gravitational wave signals. The target sensitivity for a single cluster of DECIGO is 4×10^{-24} $\mathrm{Hz}^{-1/2}$ around 1 Hz, while for two clusters at the same location with three years of correlation, it is 7×10^{-26} $\mathrm{Hz}^{-1/2}$ around 1 Hz. With this level of sensitivity, DECIGO enables a wide range of scientific investigations, including precise prediction of the location and timing of neutron star binary coalescences [13], direct measurement of the acceleration of the universe's expansion [1], elucidation of the formation mechanism of intermediate-mass black holes, detection of gravitational waves associated with primordial black holes [14], enhancement of the accuracy of general relativity [15], identification of planets around neutron stars [16], estimation of the scalar field during the electroweak phase transition [17], and examination of the gravitational lensing effect on gravitational waves [18] [19].

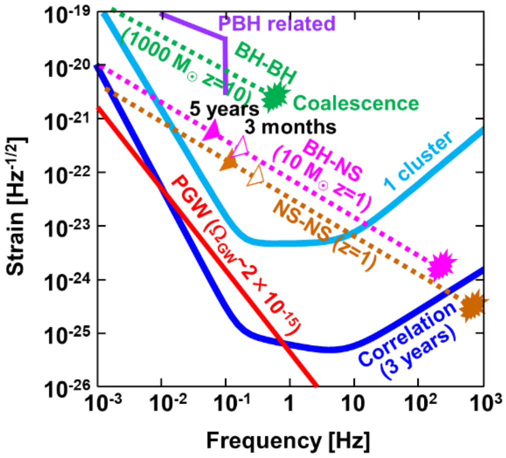

Fig.2. Target sensitivity of DECIGO and estimated gravitational wave signals.

Among these objectives, the most significant and captivating scientific achievement we anticipate with DECIGO is the detection of PGWs. The discovery of PGWs would enable us to ascertain the occurrence of inflation and determine the correct inflation model. Furthermore, we could estimate the reheating temperature of the universe by analyzing the PGW spectrum [20], detect scalar and vector modes of gravitational waves [21], and investigate the parity symmetry [22].

3. Update of design

The upper limit of PGWs around 0.1 Hz is estimated based on the upper limit of PGWs at much lower frequencies around 10^{-18} Hz obtained from observations of the electromagnetic cosmic background (CMB). The previously estimated upper limit of the normalized energy density of gravitational waves, Ω_{GW}, around 0.1 Hz was 2×10^{-15} [23] when we determined the pre-conceptual design of DECIGO around 2005. However, recent observations of the CMB by the Planck satellite [24] and other measurements [25] have reduced the upper limit of Ω_{GW} at very low frequencies, potentially decreasing Ω_{GW} around 0.1 Hz to 1×10^{-16}. Consequently, we need to improve the target sensitivity of DECIGO to enhance the possibility of detecting PGWs.

First, we investigated the dependence of the quantum-noise-limited sensitivity of DECIGO on the radius of the mirrors. Due to DECIGO's long arm length, the diffraction loss of the laser light imposes limitations on the arm length; otherwise, the loss would be too significant to achieve a cavity with a finesse of 10. Therefore, increasing the mirror diameter is expected to extend the arm length and consequently improve the sensitivity to gravitational wave signals. We optimized important design parameters (cavity length, mirror reflectivity, and laser power up to 100 W) for a given mirror radius to maximize the signal-to-noise ration (SNR) of the two clusters at the same location. The SNR is defined as follows:

$$\mathrm{SNR} = \frac{3H_0^2}{10\pi^2}\sqrt{T}\left[\int_{0.1}^{1}\frac{2\gamma^2(f)\ \ {}^{2}_{\mathrm{GW}}(f)}{f^6 P_1(f) P_2(f)}\,df\right]^{1/2} \quad . \tag{1}$$

Here, H_0 is the Hubble constant, T is the observation time (in this case, 3 years), $\gamma(f)$ is the normalized overlap reduction function (assumed as 1 in this case), P_1 and P_2 (eaqual in this case) are the power spectra of the sensitivity of a single cluster. We used the default design parameters for the mirrors (radius: 0.5 m, mass: 100 kg) and assumed a constant mirror thickness regardless of the radius. In this simulation, we considered only quantum noise (shot noise and radiation pressure noise). The SNR calculation was performed in the frequency range of 0.1 Hz to 1 Hz, as we assumed the double white dwarf (DWD) noise to be negligible above 0.1 Hz, and the expected PGW to be too small above 1 Hz. We also assumed the current upper limit of of Ω_{GW} (= 1×10^{-16}). The results are shown in Fig. 3 [26] [27] [28]. This indicates that increasing the mirror radius to 1 m (twice the size of the default design) enables an arm length extension to 5,000 km (five times longer than the default design), resulting in an improved SNR of 100 (ten times better than the default design).

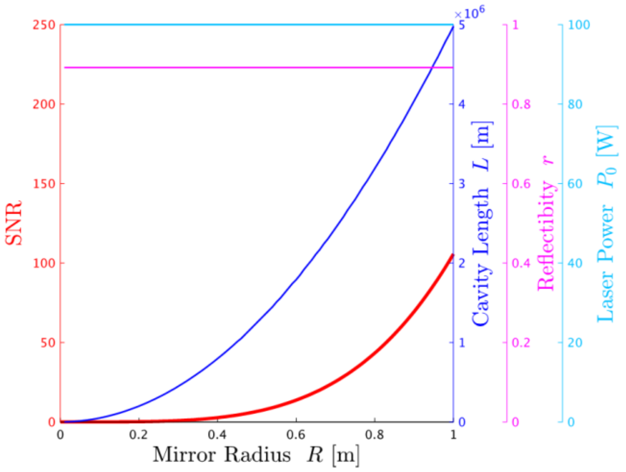

Fig.3. SNR and design parameters for a given mirror radius.

The SNR of 100 appears promising, but it is possible that the actual Ω_{GW} could be even lower. According to the inflation model proposed by Starobinsky [29], Ω_{GW} could be 1×10^{-17}. Therefore, we explored the possibility of significantly increasing the sensitivity of DECIGO by implementing optical-spring quantum locking, as shown in Fig. 4 [30] [31] [32]. Two sub-cavities are arranged in a manner where each mirror of the main cavity is shared by each sub-cavity. The main cavity mirrors are controlled by the sub-cavity control signals. The sub-cavity incorporates a homodyne detection system, and through appropriate signal combinations, the radiation pressure noise of the main cavity can be cancelled in the resulting output of the system at a specific frequency. Furthermore, the frequency width of the quantum noise dip can be broadened with the aid of optical spring achieved by detuning in the sub-cavities. We discovered that this approach can improve the SNR up to 1,000 for PGWs with Ω_{GW} of 1×10^{-16}, and 100 even for Ω_{GW} of 1×10^{-17}. These results

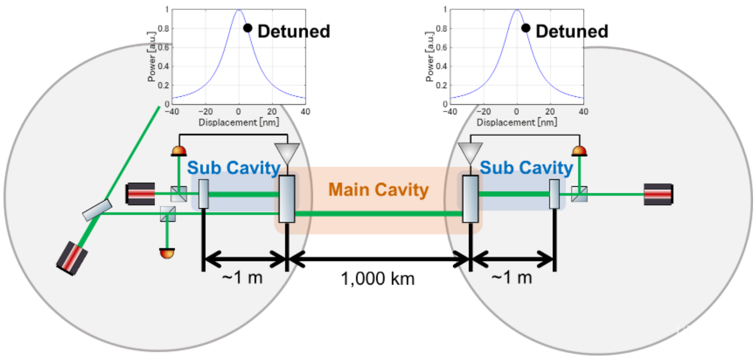

Fig.4. DECIGO with optical-spring quantum locking.

were obtained by considering only quantum noise, assuming negligible DWD noise above 0.1 Hz, and utilizing the following parameters: mirror radius of 1 m, mirror mass of 100 kg, laser power of 100 W, and arm length of 5,000 km. This SNR value is remarkably high.

4. B-DECIGO

In preparation for the realization of DECIGO, we aim to launch B-DECIGO in 2034. B-DECIGO serves as a smaller and simplified version of DECIGO, with two primary goals. The first goal is to test various technologies required for DECIGO, such as Fabry-Perot cavity control in space and foreground removal. The second goal is to contribute to significant scientific advancements, including the prediction of the timing and location of neutron star binary coalescences, exploration of the origin of 30 solar-mass black hole binaries, and improvement of parameter estimation of binaries. B-DECIGO consists of a single cluster, which shares a similar structure to DECIGO, although the specific orbit is yet to be determined. The laser power is 1 W, and the mirrors have a radius of 0.15 m and a mass of 30 kg. The arm cavity has a finesse of 100. The target sensitivity of B-DECIGO is 4×10^{-23} $\mathrm{Hz}^{-1/2}$ around 1 Hz. We have been actively developing various technologies for B-DECIGO, including dual-pass cavity control [33], low-noise thrusters [34], and high-power stabilized lasers [35].

Here, we should mention the Space Interferometer Laboratory Voyaging towards Innovative Applications (SILVIA). SILVIA is a small satellite mission candidate at ISAS/JAXA, developed in collaboration with the DECIGO working group and the infrared interferometer team. The primary goals of SILVIA include demonstrating formation flying technologies and drag-free technologies. The mission proposal was submitted to ISAS in February 2020, received approval to proceed with the idea implementation process in August 2020, and was subsequently approved to proceed with the mission definition phase in December 2022. Currently, studies for the mission definition are underway.

5. Conclusions

In conclusion, DECIGO is expected to make substantial contributions to scientific advancements, particularly in the direct detection of PGWs. To support this goal, we are actively updating the DECIGO design. Additionally, B-DECIGO serves as a critical testbed for DECIGO technologies while also enabling various scientific accomplishments, such as the frequent prediction of neutron star binary coalescences. Both missions represent significant milestones in the field of gravitational wave astronomy.

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