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The Japanese space gravitational wave antenna: DECIGO

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Abstract
The objectives of the DECi-hertz Interferometer Gravitational Wave Observatory (DECIGO) are to open a new window of observation for gravitational wave astronomy and to obtain insight into significant areas of science, such as verifying and characterizing inflation, determining the thermal history of the universe, characterizing dark energy, describing the formation mechanism of supermassive black holes in the center of galaxies, testing alternative theories of gravity, seeking black hole dark matter, understanding the physics of neutron stars and searching for planets around double neutron stars. DECIGO consists of four clusters of spacecraft in heliocentric orbits; each cluster employs three drag-free spacecraft, 1000 km apart from each other, whose relative displacements are measured by three pairs of differential Fabry–Perot Michelson interferometers. Two milestone missions, DECIGO pathfinder and Pre-DECIGO, will be launched to demonstrate required technologies and possibly to detect gravitational waves.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Gravitational waves are considered one of the most powerful future means of revealing various aspects of the universe which have not yet been observed by conventional methods. Although gravitational waves have not yet been directly detected, we should have a clear roadmap plan to lead us to a completely new astronomy, gravitational wave astronomy. The world's gravitational wave community is currently working on ground-based detectors [1] such as LIGO [2, 3], Virgo [4, 5], GEO [6, 7], LCGT [8, 9] and AIGO [10, 11] for the first detection of gravitational waves to establish gravitational wave astronomy. A space gravitational wave antenna, LISA [12–14], has also been pursued to expand the window for gravitational wave astronomy. Proposed here is another space antenna, DECi-hertz Interferometer Gravitational Wave Observatory (DECIGO), to further expand the window for gravitational wave astronomy and open fruitful avenues for science.

2. Objectives and scope

DECIGO [15–19] is the future Japanese space gravitational wave antenna. DECIGO is aimed at detecting gravitational waves mainly between 0.1 and 10 Hz, somewhat similar to BBO [20] and ALIA [21].

The objectives of DECIGO are to open a new window of observation for gravitational wave astronomy and thus to reveal a variety of secrets of the universe ranging from astrophysics to cosmology. Scientific insights obtained by DECIGO will include (1) verifying and characterizing inflation, (2) determining the thermal history of the universe, (3) characterizing

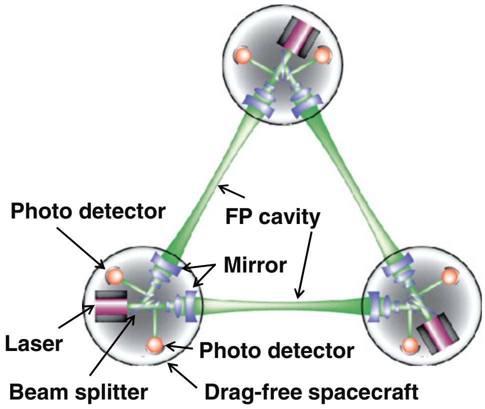

Figure 1. Pre-conceptual design of DECIGO.

dark energy, (4) describing the formation mechanism of supermassive black holes in the center of galaxies, (5) testing alternative theories of gravity, (6) seeking black hole dark matter, (7) understanding the physics of neutron stars and (8) searching for planets around double neutron stars.

It should be emphasized that the frequency band of DECIGO, 0.1–10 Hz, is appropriate to reach a very high sensitivity, since the confusion limiting noise caused by irresolvable gravitational wave signals from many compact binaries in our galaxy is expected to be very low above 0.1 Hz [22]. Note also that this frequency band is between that of LISA and ground-based detectors. Thus DECIGO will be able to play a follow-up role for LISA by observing inspiral sources that have moved above the LISA band, as well as a predictor for ground-based detectors by observing inspiral sources that have not yet moved into the ground-based detector band.

3. Pre-conceptual design

The pre-conceptual design of DECIGO is the following. DECIGO consists of four clusters of spacecraft; each cluster employs three drag-free spacecraft containing freely-falling mirrors as shown in figure 1. A change in the distance between the mirrors caused by gravitational waves is measured by three pairs of differential Fabry–Perot (FP) Michelson interferometers. The distance between the spacecraft is 1000 km, the diameter of each mirror is 1 m and the wavelength of the laser is 0.5 μm. This ensures a finesse of 10 in the FP cavities, which is determined by the diffraction loss of the laser power in the cavity. The mass of each mirror is 100 kg and the laser power is 10 W. DECIGO will be delivered into heliocentric orbits with two clusters nearly at the same position and the other two at separate positions.

We chose the FP configuration rather than the light transponder configuration because the FP configuration could provide a better shot-noise-limited sensitivity than the transponder configuration, since gravitational wave signals can be enhanced by the FP cavity. Note that the FP configuration requires a relatively short arm length to avoid the optical loss of the diverging laser light; this makes the requirement of the acceleration noise considerably stringent.

The implementation of the FP cavity using the drag-free spacecraft is feasible. Each spacecraft follows the motion of the mirror inside each spacecraft as a result of the function of the drag-free system. Each mirror is, on the other hand, controlled in position in such a way

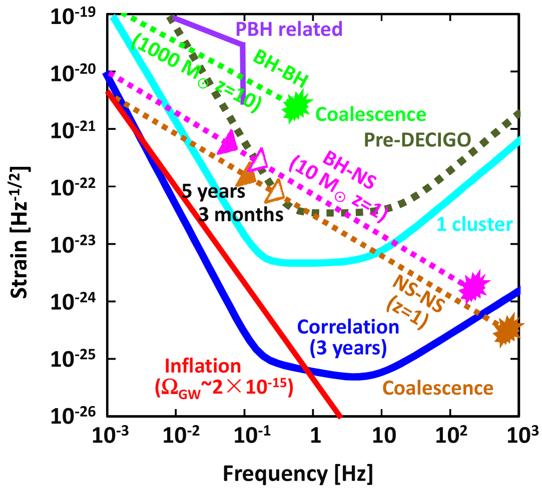

Figure 2. Sensitivity goal of DECIGO and Pre-DECIGO together with expected gravitational wave signals.

that the distance between the mirrors is maintained as a result of the function of the FP cavity. Therefore, the distance between the spacecraft is also maintained.

Since the mirrors are shared by two interferometers to form a FP cavity, the optical field from one interferometer in the cavity will leak out the end mirror, which is an input mirror for the second interferometer, and will reach the photo detector of the second interferometer. One method to avoid this undesirable interference is to keep the lasers at well-separated frequencies. Another method is to control the lasers at exactly the same frequency. We are currently optimizing the optical method for the best sensitivity of the detector.

4. Sensitivity goal

As shown in figure 2, the sensitivity goal of DECIGO is better than 10^{-23} in terms of strain between 0.1 and 10 Hz. The sensitivity is limited by the radiation pressure noise below 0.15 Hz, and by the shot noise above 0.15 Hz. The sensitivity obtained by taking the correlation between the two clusters of DECIGO nearly at the same position is also shown in figure 2. To achieve these sensitivities, we should suppress all the practical noise below the stringent requirement, especially on the acceleration noise of the mirror and frequency noise of the light.

The acceleration noise includes the noise caused by the actuator for the control of the resonance condition, thermal noise due to gas damping, especially with a small gap between the mirror and the mirror housing [23], and other practical noises. Achieving this extremely low acceleration noise in the presence of large actuating force to maintain the resonance condition requires very challenging dynamic range performance of the actuator. Fortunately, however, this stringent requirement can be significantly relieved by implementing a large loop gain of the control system at the observation band. Suppressing the thermal noise due to gas damping with a small gap also requires an extremely high vacuum level in the vicinity of the mirror and a sophisticated structure of the housing system to make the gap wider.

Frequency noise couples with a residual imbalance between the two arms to produce noise in the interferometer output. To suppress the effect of frequency noise below the aimed sensitivity, we should impose stringent requirements on the three quantities: frequency stability of the laser with the first-stage frequency stabilization, frequency stabilization gain by the common-mode arm length and common-mode rejection ratio.

5. Expected science

Once we attain the goal sensitivity of DECIGO, we can obtain a variety of fruitful science mentioned below. Here, we need to simultaneously perform these scientific studies using the same data streams of detectors. Therefore, it is critical to develop efficient data analysis methods for DECIGO, as in the case of LISA. For example, in order to detect a weak inflation background, astrophysical foregrounds should be removed down to an appropriate level. Among others, the foreground by cosmological neutron star binaries is relatively well estimated and its amplitude is expected to be at least approximately five orders of magnitude higher than that of an inflation background in terms of $\Omega_{\rm GW}$ [24].

5.1. Verification and characterization of inflation

DECIGO can detect stochastic background around 0.1–1 Hz corresponding to $\Omega_{\rm GW} = 2 \times 10^{-15}$ by correlating the data from the two clusters of DECIGO, which are placed nearly at the same position, for 3 years (see figure 2). According to the standard inflation models, we might detect gravitational waves produced at the inflation period of the universe with DECIGO. This is extremely significant because gravitational waves are the only means which make it possible to directly observe the inflation of the universe, and determine the energy scale of the inflation $E_{\rm inf}$ with a relation (see e.g. [25])

$$\Omega_{\rm GW} \sim 10^{-15} (E_{\rm inf}/2 \times 10^{16}\,{\rm GeV})^4.$$

5.2. Determination of the thermal history of the universe

DECIGO can not only observe the primordial gravitational waves generated during inflation [26] directly, but also potentially determine the thermal history of the early universe between the end of inflation and the Big-Bang nucleosynthesis [27]. The gravitational waves generated during inflation re-enter the Hubble radius with the same amplitude. Then, they start to oscillate to decrease the amplitude in proportion to $a(t)^{-1}$, where $a(t)$ is the cosmic scale factor. This simple evolution law of gravitational waves makes it possible to probe the equation of state (EOS) of the bulk energy density [27–32] and the effective number of relativistic degrees of freedom [33] by measuring the amplitude of gravitational waves at each frequency. Nakayama *et al* [28, 29] argued that DECIGO can thereby determine the reheating temperature of the inflation if it lies in the range 10^5–10^9 GeV, which is in accordance with the constraints imposed by the gravitino problem [30].

5.3. Characterization of dark energy

As shown in figure 2, DECIGO can observe gravitational waves coming from a large number of neutron star binaries for several years prior to coalescences. Their estimated merger rate at $z < 1$ is $\sim$50 000 yr^{-1} [34]. From the gravitational waveforms of individual binaries, it is possible to determine their luminosity distances in a very clean manner. By identifying their host galaxies within the expected error boxes (typically less than 10 arcsec^2) and additionally measuring their redshifts, we can observationally study dark energy only using the first principles of physics [35].

5.4. Formation mechanism of supermassive black holes in the center of galaxies

DECIGO can detect gravitational waves coming from coalescences of intermediate-mass black hole binaries with an extremely high fidelity. For example the coalescences of black hole binaries of 1000 $M_\odot$ at $z = 10$ give a signal to noise ratio on the order of 1000 (see figure 2). This will make it possible to collect numerous data about the relationship between the masses of the black holes and the frequency of the coalescences, which will reveal the formation mechanism of supermassive black holes ubiquitously observed in the center of galaxies.

5.5. Test of the alternative theories of gravity

DECIGO is very powerful in probing gravitational theories, especially Brans–Dicke theory [36]. It is the simplest type of scalar–tensor theory and the current strongest bound is obtained from the Saturn probe Cassini using Shapiro time delay [37]. This theory can be tested from gravitational wave observations of NS/BH binaries (see figure 2 for the GW spectrum of a (1.4 + 10) $M_\odot$ NS/BH binary at $z = 1$) because the binary evolution differs from that of general relativity (GR) due to the additional scalar dipole radiation [38–40]. Since a NS/BH binary signal with DECIGO has a large number of gravitational wave cycles and a wide effective frequency range for a given observation period, it has advantages for probing Brans–Dicke theory over other interferometers such as Advanced LIGO and LISA. For precessing NS/BH binaries with the predicted event rate of 10^4 per year, DECIGO can put four orders of magnitude stronger constraint than the solar system experiment [41].

While the inflation background is the primary target for the correlation analysis with the two clusters, it would be important to carefully design the system so that we can disclose various aspects of stochastic gravitational wave backgrounds. One of the interesting quantities from fundamental physics is the Stokes V parameter [42]. This parameter characterizes the asymmetry of the amplitudes of the right- and left-handed waves, and it is a powerful measure to probe violation of parity symmetry that interchanges the two circular-polarization modes. Other potential targets are the additional polarization modes (e.g. scalar gravitational waves) that are predicted by modified gravitational theory beyond Einstein's theory. If GR does not strictly hold in the high-energy regime of the universe, extra-polarization modes of gravitational waves would be produced during inflation era, together with ordinary polarizations in GR. In addition, the energy density of non-Einstein gravitational waves might exceed that of the tensor modes, depending on the coupling parameters in a specific theoretical model. Thus a search for extra-polarization modes is indispensable as a cosmological test of GR. For separate detection of each polarization mode, a detector geometrical configuration should satisfy the condition that the detectors are located away from each other at least by more than one wavelength of a gravitational wave to break the mode degeneracy. As for DECIGO, this condition can be satisfied by slightly adjusting the relative configuration of the clusters. Hence, we can decompose non-Einstein polarization modes with modest sensitivity [43].

5.6. Search for black hole dark matter

DECIGO can be a powerful probe for the abundance of primordial black holes (PBHs) [44], which are a viable candidate of the dark matter in the form of black holes. For PBH formation, large amplitude density fluctuations are required in the early universe. The required fluctuations are so large that gravitational waves are generated from them with amplitudes large enough to be detected by DECIGO as depicted in figure 2 [45, 46]. The typical frequency of the induced gravitational waves is uniquely determined by the mass of PBHs. The DECIGO band corresponds to the mass range 10^{-13}–10^{-7} $M_\odot$, which is, as yet, unconstrained by the gravitational lensing experiments [47]. Therefore, DECIGO has an ability to determine whether the PBHs are the dark matter or not.

5.7. Physics of neutron stars

The EOS of neutron stars is not yet well known. In principle, QCD Monte Carlo calculations will give us the final answer in the future but there exist difficulties with this kind of calculation. DECIGO can determine the mass of 100 000 neutron star binaries per year so that the mass spectrum of neutron stars will be measured. Especially, the maximum mass of the spectrum can constrain the EOS while the spectrum can give important information on the formation processes of neutron stars.

5.8. Planet Search with DECIGO

With DECIGO we can search circumbinary planets around double neutron stars even at cosmological distances $z{\sim}1$. The underlying approach is similar to the method used for detecting planets around a radio pulsar [48] and to observe gravitational wave modulations imprinted by wobble motions of the binaries [49]. To clearly discriminate the periodic signature of a circumbinary planet, it should orbit around the binary at least three times during the passage of the DECIGO band, corresponding to the orbital period less than 20 days for $z{\sim}1$. In this case, the combination $M_{\rm p}\sin(i)$ ($M_{\rm p}$: mass of the planet, i: its inclination angle) at $z{\sim}1$ can be estimated with better than 10% accuracy even for the mass $M_{\rm p}\sin(i)$ as small as the Jupiter mass 2×10^{30} g. Once a planet is detected with DECIGO, it would provide us with interesting information about formation and evolution of planets under extreme environments.

6. DECIGO pathfinder and pre-DECIGO

DECIGO is an extremely challenging mission. The technologies required to realize DECIGO should be obtained and demonstrated step by step. Therefore, we plan to launch two milestone missions before DECIGO: DECIGO pathfinder (DPF) [19] and pre-DECIGO.

6.1. DECIGO pathfinder

DPF will demonstrate the key technologies for DECIGO using a single spacecraft just as LISA pathfinder [50] does for LISA. The technologies to be demonstrated include the drag-free system, the FP cavity measurement system in space, frequency-stabilized laser in space and the clamp release system. DPF also has its own scientific objectives both in gravitational wave observation and measurement of the earth's gravity.

DPF is a small drag-free spacecraft that contains two freely-falling masses, whose relative displacement is measured with a FP interferometer with a frequency-stabilized laser. The masses are clamped tightly for the launch and released gently in space. The optical and mechanical parameters of DPF are 30 cm for the cavity length, 1 μm and 25 mW for the laser wavelength and power, respectively, 100 for the finesse of the FP cavity and 1 kg for the mirror mass. The strain sensitivity of DPF will be about 10^{-15} between 1 and 10 Hz, as

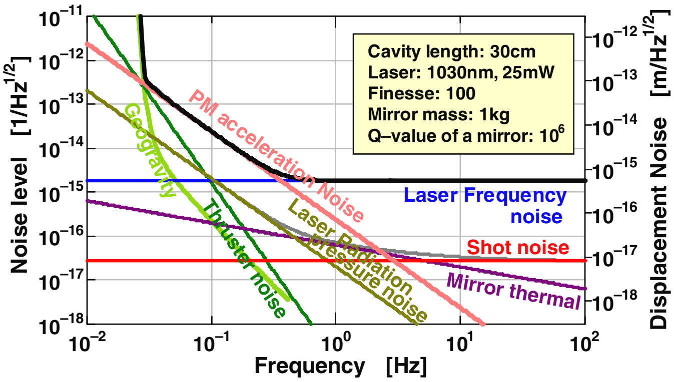

Figure 3. Goal sensitivity of DECIGO pathfinder together with the estimated noise.

shown in figure 3. This sensitivity is limited by the frequency noise of the laser, because there is only one arm cavity in DPF. All the other noise sources such as the acceleration noise and thermal noise should be suppressed with an appropriate design. DPF will be delivered into a geocentric sun-synchronous orbit with an altitude of 500 km.

The primary scientific objective of DPF is to perform an observation run for gravitational waves down to 0.1 Hz with a possibility of detection of gravitational waves coming from rather unlikely events of intermediate-mass black hole inspirals in our galaxy. Although the probability of having such events is considered to be rather rare, data obtained by DPF observations will be quite important since this observation band is difficult to access by ground-based gravitational-wave detectors.

The secondary scientific objective of DPF is to measure the earth's gravity. Since the proof masses of DPF orbit around the earth almost freely, gravity distributions of the earth can be measured from the trajectories of the proof masses. DPF is expected to provide data whose sensitivity is comparable with that provided by other earth gravity measurement missions, such as GRACE [51], Champ [52], and GOCE [53].

We have been developing the required technologies of DPF intensely. We have already made significant progress in the breadboard model of most of the subsystems, such as the interferometer system, test mass module, and laser and frequency stabilization system. We plan to launch DPF with the small-spacecraft science mission run by the Japanese space agency, JAXA/ISAS. DPF was one of the two final candidate missions for the second mission, but unfortunately it was not selected. We will submit a proposal for the third mission in 2011, expecting that it will be launched in 2015.

6.2. Pre-DECIGO

The objectives of Pre-DECIGO are scientifically to detect gravitational waves with modest optical parameters, and technologically to demonstrate the technologies of formation flight using three spacecraft. Pre-DECIGO is designed to have a sensitivity that is conservative compared with DECIGO by a factor of 10–100. Accordingly, the optical parameters and the noise requirements of Pre-DECIGO are less stringent than DECIGO. Pre-DECIGO consists of three drag-free spacecraft containing freely-falling mirrors, whose relative displacement is measured by a differential FP Michelson interferometer. The distance between the spacecraft is 100 km, the diameter of the mirror is 0.3 m and the wavelength of the laser is 0.5 μm. This corresponds to a finesse of 100 in the FP cavities. The mass of the mirror is 30 kg and the laser power is 1 W. The goal sensitivity as shown in figure 2 will ensure detection of gravitational waves coming from neutron star binaries as far as 300 Mpc. We hope to launch Pre-DECIGO in 2021.

7. Conclusions

The future Japanese space gravitational wave antenna, DECIGO, is expected to detect gravitational waves from various sources and provide a variety of fruitful science, and thus to open a new window of observation for gravitational wave astronomy. We plan to launch two milestone missions before DECIGO to demonstrate required technologies and possibly to detect gravitational waves: DPF and Pre-DECIGO.

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