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JAPANESE SPACE GRAVITATIONAL WAVE ANTENNA DECIGO AND DPF

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ABSTRACT

The gravitational wave detection will open a new gravitational wave astronomy, which gives a fruitful insight about early universe or birth and death of stars. In order to detect gravitational wave, we plan a space gravitational wave detector, DECIGO (DECI-hertz Interferometer Gravitational wave Observatory), which consists of three drag-free satellites forming triangle shaped Fabry-Perot laser interferometer with the arm length of 1000 km, and whose strain sensitivity is designed to be $2 \times 10^{-24} / \sqrt{\text{Hz}}$ around 0.1 Hz. Before launching DECIGO around 2030, a milestone mission named DECIGO pathfinder (DPF) is planned to be launched whose main purpose is the feasibility test of the key technologies for DECIGO. In the present paper, the conceptual design and current status of DECIGO and DPF are reviewed.

I. INTRODUCTION

The motion or time variation of the mass will cause the ripples in gravitational fields, and it propagates as wave, which is called gravitational wave (GW). GW has been predicted by A. Einstein in his general theory of relativity, and the direct detection of GW will give us much different information from those obtained by conventional electric-magnetic waves, and open a new window of gravitational wave astronomy. As the expected strain caused from GW is, however, smaller than $dl/l < 10^{-22}$, the direct detection of GW has hardly been achieved before. Since GW would be detected as tidal-force fluctuations on two proof masses, many trials have been done for direct detection of GW by using long-baseline laser interferometers, and next generation terrestrial laser interferometers with higher sensitivity are going to start operating in this decade, such as KAGRA in Japan [1], adv.LIGO in USA [2], and adv.VIRGO in Europe [3] with the arm length of 3-4 km and the Fabry-Perot cavities are installed in their arms to extend the effective arm length. The detection bandwidth of the terrestrial GW detector is from 10 Hz to 1 kHz, and the targets of these detectors are GW emitted from explosion of supernovae or inspiral and merger of the neutron-star binaries. The observation bandwidth of the terrestrial GW detector at lower frequency range is limited by the gravity gradient noise or seismic noise. At lower frequency range below 1 Hz, however, the fruitful GW sources are expected which is different from those obtained by terrestrial GW detectors and which gives us the insight about early universe or massive black holes. In order to observe GW at lower frequency range, the space gravitational wave detectors are planned which have lower frequency observation band because they can have much longer arm length and are free from gravity gradient noise and seismic noise from the ground. Currently, three main space GW detection missions are planned. eLISA (Evolved Laser Interferometer Space Antenna) [4] is a European space GW antenna with the observation band of 1 mHz, and BBO (Big Bang Observatory) [5] is a following mission of eLISA. DECIGO [6] is Japanese space gravitational wave detector whose detection band is between those of eLISA and terrestrial detectors. Such space gravitational wave detectors are large missions in the aspects of resources and technical issues, each project has their own milestone mission: LPF [7] for eLISA, and DPF [8] for DECIGO. In the present paper, the conceptual design, scientific objects and current status of DECIGO and DPF are reviewed.

II. DECIGO

DECIGO (DECI-hertz Interferometer Gravitational wave Observatory) is Japanese space gravitational wave antenna which is planned to be launched around 2030. DECIGO is a triangle-shaped laser interferometer with the arm length of 1000 km, and Fabry-Perot cavities are installed in each arm. The strain sensitivity of GW detectors is shown in Fig.1. The sensitivity of the laser interferometric gravitational wave detector at lower frequency is limited by the external perturbations to the mirrors, which can be improved by extending the arm length, and the sensitivity at higher frequency range is limited by photon shot noise. Compared with eLISA which is a 1000000-km triangle shaped laser interferometer with optical transponder configuration, the sensitivity of DECIGO at lower frequency range is worse than that of eLISA. On the other hand, the arm length of 1000 km is short enough to avoid diffraction loss of the laser light, and the Fabry-Perot configuration stores much more photons in their arms. Therefore, shot-noise limited level of DECIGO at higher frequency range is much better than that of eLISA.

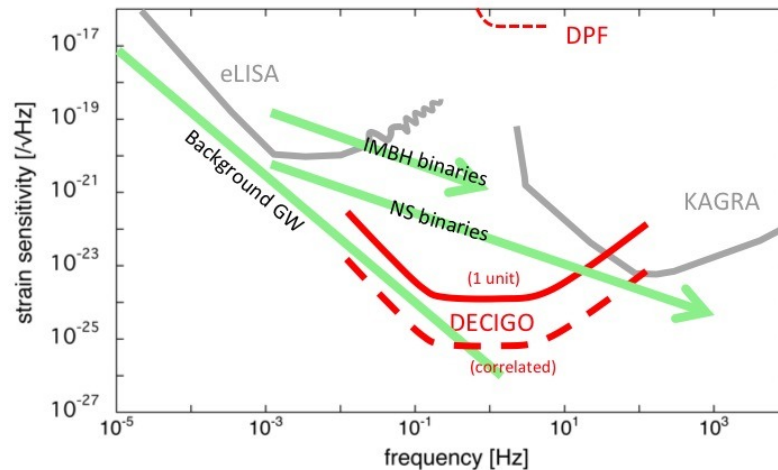


Fig.1 Strain sensitivity of GW detectors and their targets of GW sources;
IMBH: intermediate-mass blackhole, NS: neutron star

In the consequences, the observation band of the DECIGO, (0.1 Hz-1 Hz), stays between that of eLISA (1mHz) and ground-based GW detectors (<10Hz), and the strain sensitivity of DECIGO is design to be $\delta l/l=2 \times 10^{-24} \sqrt{\text{Hz}}$ at this frequency range. (see fig.1)

A. Scientific target

With the strain sensitivity at this frequency range, DECIGO has three main target sources: intermediate mass blackhole mergers, distant neutron-star binaries and stochastic background of the GW signal from the early universe, the detection band of which is free from the confusion noise by irresolvable GW signal from too many white dwarf binaries. Since the inspiral and mergers of intermediate mass (10^3 - $10^5 M_{\odot}$) blackholes and these multiple collisions are expected to result in supermassive blackhole in the center of galaxy, the detection of GW from intermediate-mass blackholes will lead us to the inspection of the forming mechanism of the supermassive blackhole in the galaxy [9]. GW signals from many distant neutron-star binaries, whose distance is redshift of 1 and the number of which are about 3×10^5 , will give us the information of mass distributions of neutron stars. The stochastic background GWs from the early universe are most interesting target. These signals are originated from inflation, primordial blackholes, or astrophysical object in the early universe, and we can investigate these phenomena only by observing GW because the electro-magnetic wave could not be propagated due to high-energy plasma filled in the early universe. In addition, space gravitational wave detector will be a predictor for the terrestrial GW antenna by detecting binary inspiral sources [10].

B. Conceptual design of DECIGO

The preconceptual design of DECIGO is shown in Fig.2. DECIGO consists of three drag-free spacecrafts, and each satellite contains the proof mass mirror and the frequency-stabilized laser, forming a triangle-shaped laser interferometer with the arm length of 1000 km. The proof mass mirrors are highly-reflective mirrors with the diameter of 1 m and the weight of 100 kg, and each two of them form Fabry-Perot cavity with the Finesse of 10. As the proof mass mirrors in the drag-free spacecrafts act as free mass in space, the distortion of the space caused by GW is detected as the changes of the cavity length. The light source is single-frequency continuous wave (cw) lasers with the wavelength of 515 nm, and the power of 10 W. Details of the light source are described in ref.11. 1000-km arm length with Fabry-Perot configuration is optimized for realizing high strain sensitivity of $2 \times 10^{-24} \sqrt{\text{Hz}}$ at the observation frequency around 0.1 Hz, whose detection band is much higher than that of eLISA (1mHz). In the final stage of DECIGO project, four interferometer units will orbit around the sun along the earth orbit for minimizing the gravity disturbances from the sun and planets so as to distinguish stochastic background GW from detector noise by cross-correlation observation.

Fig.3 shows the roadmap to realize DECIGO. DECIGO is very large mission which requires a lot of resources, and there are many technical difficulties to be overcome such as formation flight with 1000-km separation, precision drag-free control, space-borne stabilized light source, and so on.

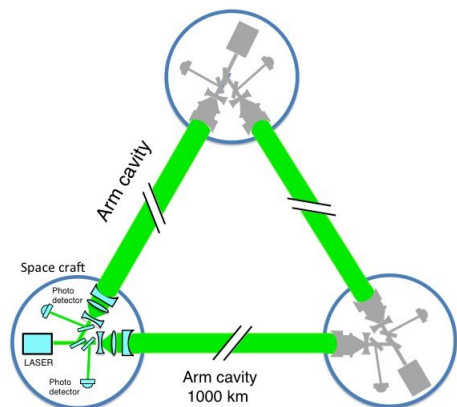


Fig.2 Conceptual design of DPF

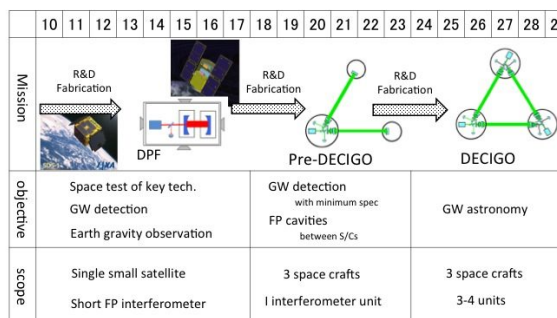


Fig.3 Roadmap to realize DPF

Therefore, two milestone missions are planned before launching DECIGO around 2030. The second milestone mission is Pre-DECIGO which have down-sized configuration of DECIGO, comprised of three drag-free spacecraft with 100-km separation, and whose purpose is to establish the distant formation flight technique and detection of GW with minimum specifications. The first milestone mission is DECIGO pathfinder called DPF, details of which are described in the following session.

III. DPF (DECIGO pathfinder)

DECIGO pathfinder (DPF) is a first milestone mission of DECIGO which is planned to be launched after 2019. DPF is a single small satellite whose mission payload is 400 kg and the size of mission part is 950x950x900 mm. In order to achieve thermal equilibrium and stable power supply, it is planned to have a circular sun-synchronous dawn-to-dusk orbit around the earth with the altitude of 500 km. DPF will be launched by a next-generation solid propelled rocket named Epsilon Launch Vehicle by JAXA (Japan Aerospace Exploration Agency).

A. Mission design of DPF

The conceptual design of DPF is shown in Fig.4. DPF consists of a frequency-stabilized laser and two drag-free proof mass mirrors with 30-cm separation, forming a Fabry-Perot cavity, and is designed for two purposes; the feasibility tests of the technical issues for DECIGO and the achievement of scientific results. The feasibility tests planned to be done with DPF are stable operation of a space-borne frequency-stabilized laser, precision drag-free control of the proof masses, and the precision interferometric measurement by using a Fabry-Perot cavity in space. The light source for DPF is a frequency-stabilized laser with the wavelength of 1 μ m and the output power of 20 mW whose frequency stability should be higher than $1 \times 10^{-15} / \sqrt{\text{Hz}}$ at Fourier frequency of 1 Hz. For realizing the required light source, we have developed a compact iodine-stabilized Yb-doped fiber DFB laser with the wavelength of 1030 nm whose second-harmonics is stabilized in reference to the saturation absorption of iodine molecules at 515 nm [11]. Since the required frequency stability of the light source for DECIGO is the same as that for DPF and the output power for DECIGO should be higher, the increasing of the output power of the DPF laser will lead to the development of DECIGO light source, in which laser power is amplified by using an Yb-doped fiber amplifier with keeping its frequency stability.

In order to keep two proof mass mirrors as a free mass, the drag free control system will be applied to DPF for isolating them from external disturbances caused by solar radiation pressure or drag from residual atmosphere along the orbit. Each proof mass mirror is contained inside a module named housing. Electrostatic-type local sensors and actuators are attached to a frame of the housing, and these sensors monitor the relative motion between mirrors and housing. The control signals are applied to the electrostatic actuators and small mission-thrusters to control the position of a spacecraft to follow the proof mass mirrors in all degree of freedom. No momentum wheels are used so as to avoid their mechanical disturbances. The fluctuations of the DPF spacecraft will be stabilized to smaller than $10^{-9} \text{ m}/\sqrt{\text{Hz}}$ by the drag-free control. DPF will demonstrate the drag-free control in an Earth orbit with the help of passive attitude stabilization by gravity-gradient of the Earth, which will be an original scheme and may open a new possibility of zero-gravity environment in space.

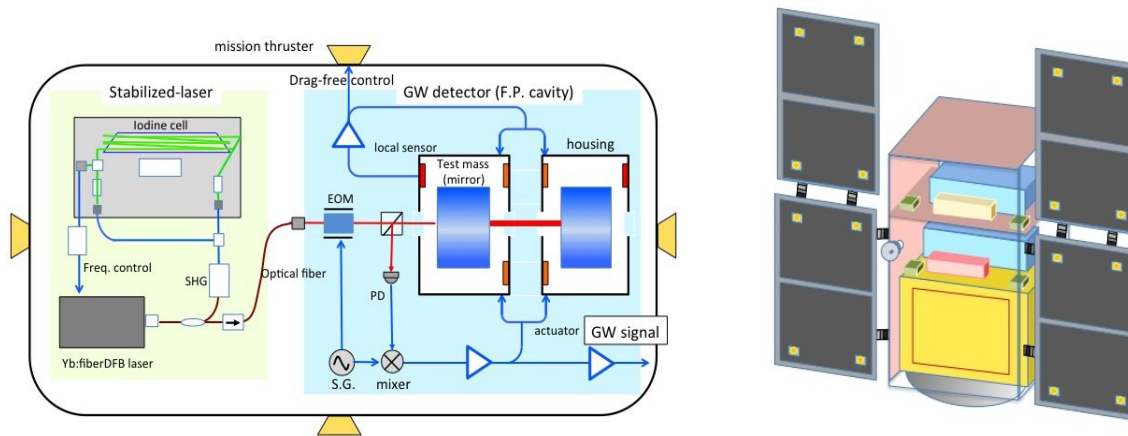


Fig.4 Diagram of mission payload of DPF (left), and overview of DPF satellite (right)

B. Science target of DPF

Besides acting as a precision interferometric measurement test bench, DPF has following scientific targets. As a gravitational wave detector, DPF has the strain sensitivity of $\delta l/l = 2 \times 10^{-15} / \sqrt{\text{Hz}}$ at the frequency around 0.1-1 Hz. At this frequency range, DPF is expected to detect GW from intermediate-mass blackhole inspiral and mergers with 10^3 - $10^4 M_o$ in our galaxy. Though the probability of these events is estimated to be low, the data observed by DPF would be important whose frequency band is hardly accessed by other space or ground-based gravitational wave detectors.

The gravity distribution of the Earth would be also observed by DPF from the trajectories of the proof mass because the drag-free proof mass mirrors orbit the Earth freely along the gravity fields. The relative displacements between the proof masses and the spacecraft are measured by small Michelson laser interferometer with the acceleration sensitivity of 10^{-11} m/s^2 . With the comparable sensitivity, DPF is expected to bridge the time gap between the current and the next-generation missions for Earth's gravity observation (GOCE, GRACE and GRACE-FO).

IV. CONCLUSIONS

The space gravitational wave detector, DECIGO, are the fruitful and ambitious mission, which open a new window of gravitational wave astronomy and will give us deep insight about the birth and death of stars, and especially about very early universe. To realize gravitational wave observation by DECIGO, there is a long way to be promoted. We have started the space gravitational wave detection project from a small demonstration mission named SWIM (Space Wire Interface demonstration Module) which was launched in 2009 in SDS-1 (JAXA's technical demonstration satellite) and was successfully demonstrated the sensing and control of proof mass for a year [12]. We are now undergoing to develop the first milestone mission of DECIGO named DPF with the support of JAXA. Research and development are underway concerning the mission studies including satellite design, drag-free control, housing system for proof masses, a frequency-stabilized laser and mission thrusters.

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