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The Taiji program: A concise overview

Ziren Luo[1,2,3,4], Yan Wang[2], Yueliang Wu[2,3,4,5,*], Wenrui Hu[1,2], and Gang Jin[1,2,3,4,*]

[1]*Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190 China*
[2]*Taiji Laboratory for Gravitational Wave Universe, University of Chinese Academy of Science, Beijing, 100049 China*
[3]*International Centre for Theoretical Physics Asia-Pacific, UCAS, Beijing 100190 China*
[4]*Faculty of Fundamental Physics and Mathematical Sciences Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024 China*
[5]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190 China*
*E-mail: ylwu@itp.ac.cn, gajin@imech.ac.cn

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Taiji is a Chinese space mission to detect gravitational waves in the frequency band 0.1 mHz to 1.0 Hz, which aims at detecting super (intermediate) mass black hole mergers and extreme (intermediate) mass ratio in-spirals. A brief introduction of its mission overview, scientific objectives, and payload design is presented. A roadmap is also given in which the launching time is set to the 2030s.

Subject Index F30, H22

1. Introduction

In 2016, the ground-based detector LIGO announced its first detection of gravitational waves (GWs) [1], the tiny variation of spacetime curvature predicted by Albert Einstein a century ago. Three of LIGO's founders won the 2017 Nobel Prize in physics for the groundbreaking discovery. The most sensitive band of LIGO is between 10 and 10^4 Hz, which makes LIGO a perfect probe of the mergers of small black holes and compact stars [2]. Space-borne gravitational wave antennas, with much longer effective arm length, are more sensitive to lower-frequency GW signals which range from 10^{-4} to 1 Hz. The first, and as yet the most feasible, space-borne GW detection mission is the Laser Interferometer Space Antenna (LISA) [3,4], a joint ESA/NASA mission planned to be launched in 2034.

Chinese scientists also showed interest in space-borne GW detection programs and considered developing independent missions in the early 2000s. After a few years' feasibility study, a preliminary mission proposal [5] based on the Advanced Laser Interferometer Antenna (ALIA) [6] was presented in 2011. With a very stringent noise budget (one hundred times more sensitive than LISA at 0.1 Hz) and a half-million-kilometer arm length, it was very sensitive to intermediate mass black hole mergers. Though the technological requirement was already much more relaxed than the Big Bang Observatory (BBO) [7] and the Deci-hertz Gravitational-wave Observatory (DECIGO) [8], it was unlikely to be met in the near future. In order to bring about a reasonable Chinese mission design which could be realized in the next few decades, the Chinese scientists had to confront the task of mission descoping.

In 2012, the first mission descoping attempt was reported to prefer a constellation of three satellites separated each by about 3 million kilometers, coordinating both technical and scientific goals, and the proposed three-step road map was first presented in which the launch time for the Chinese space

GW detector was expected to be in the 2030s [9], so that Taiji can have a few years overlap with LISA which can help to quickly and accurately localize the gravitational wave sources [10]. With the aid of prototypes built by the Chinese Academy of Science, proof-of-principle experiments for some key technologies were carried out [11–14]. Much progress was made in the studies [15–17]. Based on the knowledge obtained, a few choices for mission descoping were listed in Ref. [18]. The arm length of three million kilometers was shown to relieve the laser metrology system from the sub-picometer requirement. Even with the most modest mission design parameters, the major scientific goals could still be reached. The reasonable Chinese mission design has been made more and more complete and acceptable, and was released in 2016 as the Taiji program [19].

The Taiji program with its three-step road map has obtained priority support since 2016 for its pre-experimental study from the strategic priority research program of the Chinese Academy of Sciences. Some key technologies have been developed further in the studies [20–26]. In 2018, Taiji was further funded by the Chinese Academy of Science to carry out on-ground testing of key technologies needed for the Taiji mission and to perform the first step of launching a satellite, Taiji-1, as the Taiji pre-pathfinder for testing some important individual technologies. Meanwhile, it is going to prepare the second step by launching two satellites, Taiji-2, as the Taiji pathfinder, covering almost all the Taiji technologies.

This paper is arranged as follows. In Sect. 2 we will give a brief overall introduction to Taiji. In Sect. 3, the mission design parameters and possible scientific reach will be presented. In Sect. 4 we will briefly sketch the measurement principles and the payload design for Taiji. A planned schedule for Taiji will be given in Sect. 5.

2. Mission overview

Similar to LISA, Taiji consists of three satellites. Each satellite follows a heliocentric orbit. The three satellites form a giant equilateral triangle with an arm length of approximately 3 million kilometers. The center of mass of the constellation trails (or leads) the Earth by about 18 to 20 degrees, and is about 1 au away from the Sun; see Fig. 1.

The choice of trailing (or leading) angle is a compromise between orbit injection costs and Earth–lunar system disturbance. The eccentricity of each satellite's orbit is around 10^{-3} in order to maintain the breathing angle within the scale of ± 0.5 degree and the Doppler shifts between spacecraft within ± 5 MHz during the Taiji's five-year lifetime. The heliocentric orbit, unlike a geocentric orbit, can have another bonus in that the sun-pointing angle of the satellite is very stable within Taiji's sensitive frequency band. Therefore, the external heat flux fluctuation of each satellite can be minimized, which offers Taiji a very pleasant thermal environment. The relative arm length change of the constellation in the 10^{-3} to 1 Hz range could be very stable, enabling us to sense GWs with a strain as small as 10^{-20} [27].

If both launch according to plan, Taiji and LISA will have a few years of overlapped observing time. Since LISA has already chosen an Earth-trailing orbit, Taiji may take an Earth-leading orbit. In that case, we will have two space detectors at the same time separated by 100 million kilometers. This combined configuration may have some advantage for the detection and localization of burst and unmodeled sources.

3. Scientific objectives and baseline design

The primary target GW sources of Taiji are super and intermediate mass black hole mergers. It was believed that in the early universe, due to the metal deficiency, very massive stars (Pop III stars)

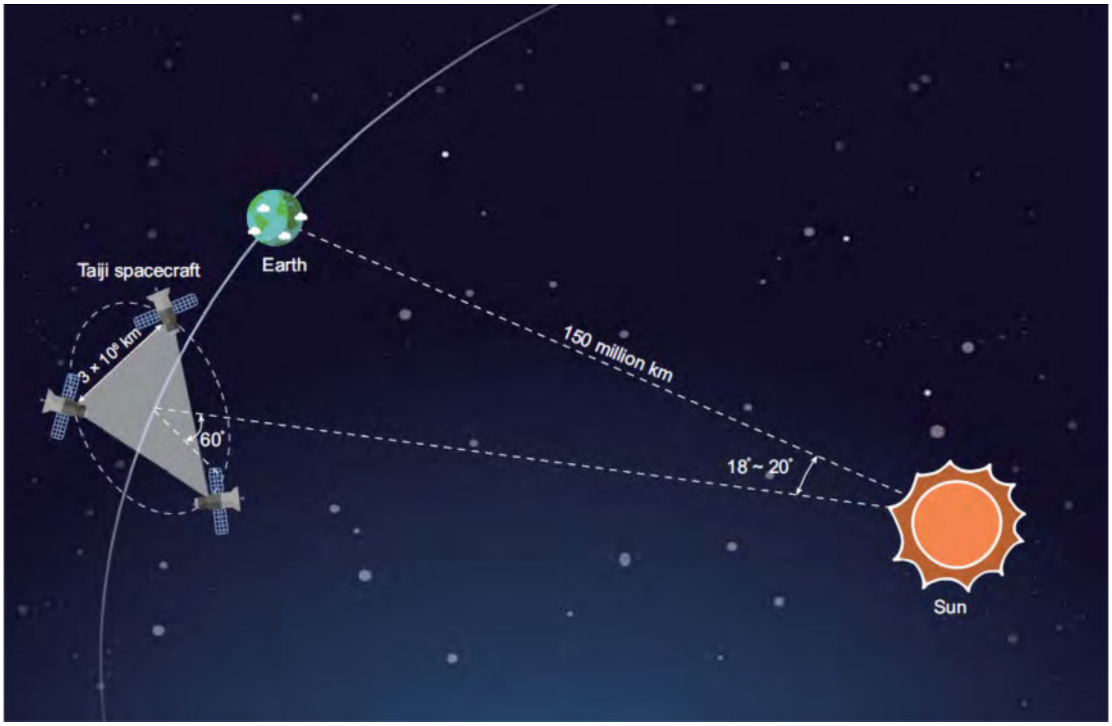

Fig. 1. Taiji constellation [19].

could form. Such a star will collapse directly into an intermediate mass black hole at the end of its lifetime [28]. Colliding and accreting, these black holes will slowly grow into supermassive black holes harbored in the centers of galaxies. Taiji can probe the complete history, shedding light on the problems of the evolution and death of Pop III stars, galactic merger and galaxy evolution, large-scale structure formation and evolution, etc. [29].

Extreme and intermediate mass ratio in-spirals are another type of interesting source. Unlike merger events, in-spiral events can last for years, allowing long integration time observations. With such data we can extract information on the source very precisely, which allows us to study the strong field structures close to massive black holes [29,30]. These events commonly take place at the centers of galaxies. Detection by Taiji gives us an alternative way to unveil the mystery of galactic nuclei. The position and time of the disruption of a small compact object by the massive black hole's tidal force can also be accurately determined, so that Taiji can forecast the electromagnetic follow-up of this tidal disruption event [31].

Galactic binaries are also located in Taiji's sensitive band. Enormous in population, most Galactic binary sources cannot be resolved, forming a GW foreground for Taiji as well as for LISA. However, the resolvable binaries could be located by Taiji. The distribution of such compact objects in the Milky Way can help us to understand the evolution of the stars in the Milky Way and the Milky Way itself.

Other Taiji GW sources could be the stochastic GW background and unmodeled sources. The stochastic GW background is multifold. Primordial gravitational waves, primordial black hole binaries, and intergalactic compact star binaries all contribute to the stochastic background. The detection of such a background would have a profound impact on early-universe cosmology, on the nature of gravity, and on high-energy physics [32,33]. The unmodeled sources, on the other hand, are difficult

Table 1. The baseline design parameters.

Missions	Position noise	Acceleration noise	Arm length	Laser power	Telescope diameter
Taiji	8 pm $\text{Hz}^{-1/2}$	3×10^{-15} ms^{-2} $\text{Hz}^{-1/2}$	3×10^{9} m	2–3 W	$\sim$ 40cm
ALIA descope	5–8 pm $\text{Hz}^{-1/2}$	3×10^{-15} ms^{-2} $\text{Hz}^{-1/2}$	3×10^{9} m	2 W	45–60 cm
ALIA	0.1 pm $\text{Hz}^{-1/2}$	3×10^{-16} ms^{-2} $\text{Hz}^{-1/2}$	5×10^{8} m	30 W	100 cm

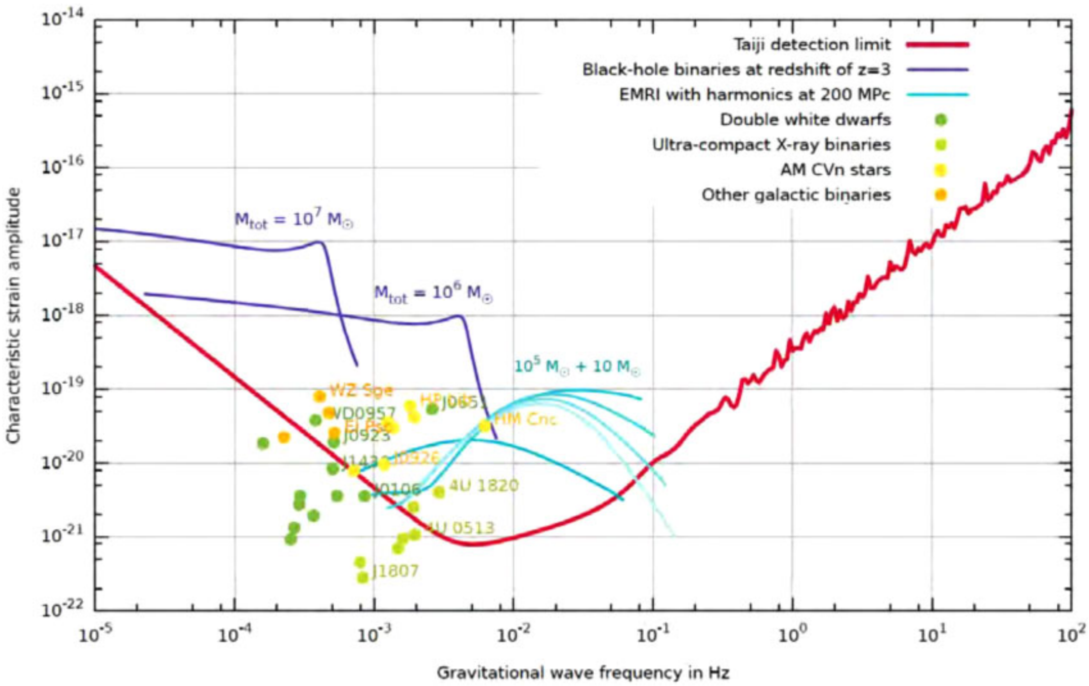

Fig. 2. The sensitivity curve of Taiji (red curve). The mass ratio is assumed to be 1:1 for black hole binaries. AM CVn stars are a rare type of cataclysmic binary believed to consist of two white dwarfs.

to predict and cannot be expected; however, they always indicate new astronomical discoveries. Thus, the unmodeled sources should also be studied carefully.

Based on previous studies [29], a modest choice of the position noise and the acceleration noise budget can achieve the above scientific objectives. The baseline design parameters for Taiji and a comparison with previous designs are given in Table 1.

On the basis of the recent progress of Taiji's laser development [25], we intend to increase the laser power to about 3 W so that we can reduce the size of the telescope, which in turn will reduce the difficulty of telescope manufacture. Assuming an integration time of one year, the relevant sensitivity curve is displayed in Fig. 2. The curve is averaged over the GW source's sky position and polarization, and only one Michelson-type variable is used for simplicity. The major GW sources are well within Taiji's detecting capability.

4. Measurement concepts and payload design

With three satellites, Taiji can have three Michelson-type interferometric signals. For example, one laser on one spacecraft is set as a master, while the other laser on the same spacecraft is phase locked to that master. A beam is sent out from the master laser, and the laser in the distant spacecraft is phase locked to the incoming beam and returns a high-power phase replica. When that beam returns

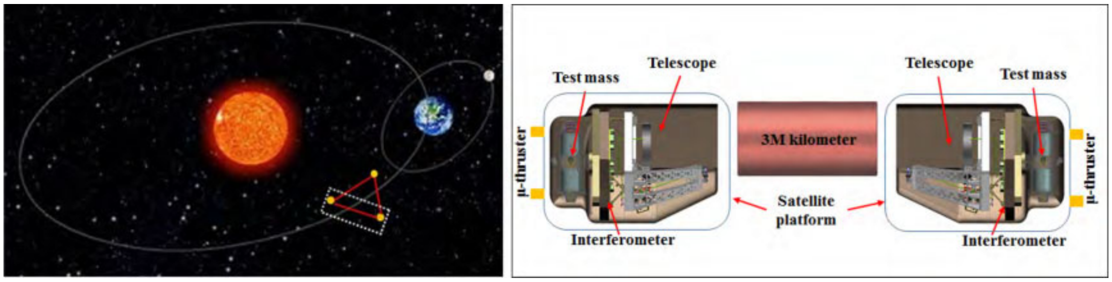

Fig. 3. Inter-satellite laser interferometry for Taiji. (Left): The Taiji constellation. (Right): A schematic diagram of the inter-satellite laser link.

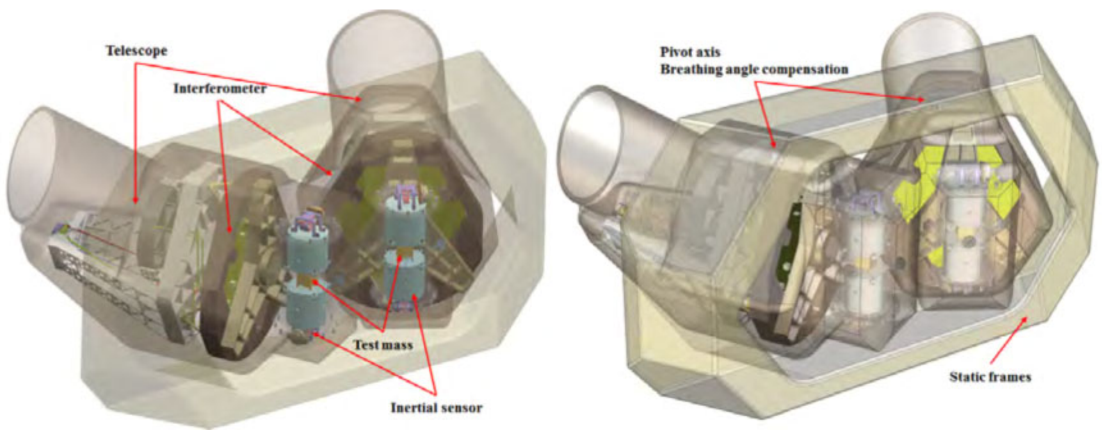

Fig. 4. Preliminary payload design for Taiji. The telescope, interferometer, test mass, and inertial sensor are shown on the left; the pivot axis of the breathing angle compensation structure and static frames are shown on the right.

to the original spacecraft, it beats with the local laser, generating a heterodyne beat note. Thus, the lasers at each end of each arm operate in an optical transponder mode.

When a GW train passes the Taiji constellation, it causes a small variation in the distance between two test masses separated by three million kilometers. The optical detection of fluctuations in the distance between the two test masses of each interferometer arm is separated into three measurements: local test mass to local interferometer, local interferometer to remote interferometer, remote interferometer to remote test mass (as illustrated in Fig. 3; for more detailed information please refer to Fig. 3.3 in Ref. [4]). The phase of the beat note contains the GW signal, and the beat note will be sent to the phasemeter where the GW signal can be decoded. The telescope transmits/receives laser light to/from remote spacecraft.

To protect the test mass from non-conservative force disturbances, a so-called drag-free control technique has to be used. The test mass together with a capacitive sensing system form an inertial sensor system which reads the relative motion between the test mass and the spacecraft. This relative motion will be fed to the drag-free controller, and the controller will command the μN thruster to push the spacecraft to follow the trajectory of the test mass, keeping the test mass in a freely floating state. The test mass is a gold platinum alloy cube with 46 mm side length, and weighs about 1.93 kg.

The preliminary payload design for a Taiji satellite is illustrated in Fig. 4 (several parts are not shown). The general requirements for Taiji payloads are listed in Table 2 (the quantities in terms of spectral density were evaluated between 1 mHz and 1 Hz).

Table 2. Preliminary payload requirement.

Laser	Wavelength: 1064 nm Frequency stability: 30 Hz $Hz^{-1/2}$ Relative intensity stability: 10^{-4} $Hz^{-1/2}$ Angular jitter (deliver to optical bench): 1 μrad $Hz^{-1/2}$
Telescope	Optical path-length stability: 1 pm $Hz^{-1/2}$ Angular jitter (outgoing beam): 1 nrad $Hz^{-1/2}$ Field of view (acquisition): 400 μrad Field of view (in plane): ±4.2 μrad Field of view (out of plane): ±7 μrad
Interferometer	Optical path-length noise: 1 pm $Hz^{-1/2}$ Differential wavefront sensing: 1 nrad $Hz^{-1/2}$ Stray light noise: 1 pm $Hz^{-1/2}$ Tilt to length noise: 1 pm $Hz^{-1/2}$ Fiber and electronics noise: 1 pm $Hz^{-1/2}$; Unknown noise (seen in experiments but not identified): 1∼3 pm $Hz^{-1/2}$ Auxiliary functionality: Reference interferometer, acquisition sensing, pointing ahead angle mechanism, inter-satellite ranging, clock noise transferring, clock synchronization, arm-locking (Opt.), inter-satellite communication
Phasemeter	Phase readout noise: 1 pm $Hz^{-1/2}$ Beat frequency range: 2–20 MHz; Frequency sweeping: 1–3 Hz s^{-1}
Inertial sensor	Test mass residual noise: 3×10^{-15} ms^{-2} $Hz^{-1/2}$ Capacitive sensing (sensitive axis): 1.8 nm $Hz^{-1/2}$ Capacitive sensing (non-sensitive axis): 3 nm $Hz^{-1/2}$ Voltage stability: 10^{-6} V $Hz^{-1/2}$ Vacuum: 10^{-6} Pa Charge management: $<10^{-7}$ C
μN thruster	Average force: >10 μN Resolution: 0.1 μN Noise: 0.1 μN $Hz^{-1/2}$ Response time: <0.33 s
Drag-free controller	Residual displacement noise (spacecraft, sensitive axis): 2 nm $Hz^{-1/2}$
Platform	Temperature stability (core payload): 10^{-6} K $Hz^{-1/2}$ Residual magnetic field (core payload): 10^{-6} T Magnetic field stability (core payload): 10^{-7} T $Hz^{-1/2}$ Gravity gradient (between two test masses): 10^{-9} ms^{-2} $Hz^{-1/2}$

5. Road map with Taiji pre-pathfinder (Taiji-1) and Taiji pathfinder (Taiji-2)

According to the initial plan of the Chinese Taiji mission, Taiji is to be launched around 2033. A road map towards Taiji's final goal is given in Fig. 5. The first step is to develop and test Taiji's key technologies in ground laboratories. Like the LISA pathfinder [34], before we eventually launch Taiji, a pair of technology demonstration satellites called the Taiji pathfinder (Taiji-2) is planned to be launched between 2023 and 2024. After the technological obstacles are cleared by the Taiji pathfinder, the complete Taiji constellation (Taiji-3) could be launched in the early 2030s. Since we have never launched a scientific satellite with such high measurement precision, a pre-pathfinder mission called Taiji-1 is arranged to explore how feasible the roadmap is. The purpose of Taiji-1 is to find out the distance from our recent capability to the final Taiji requirement.

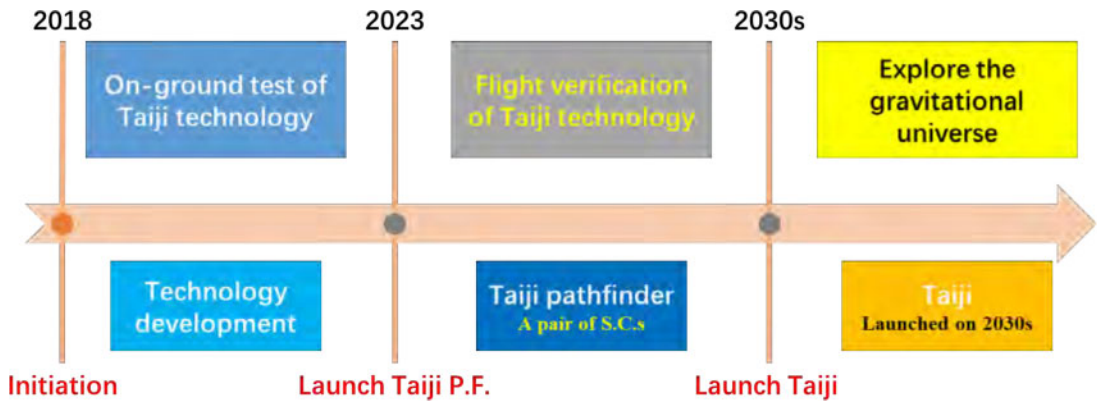

Fig. 5. The Taiji roadmap.

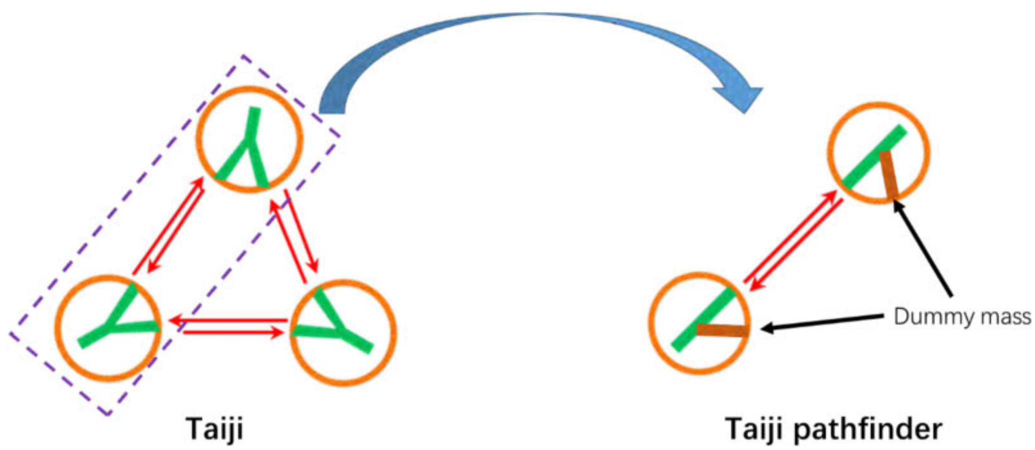

Fig. 6. The Taiji pathfinder (Taiji-2) mission design.

The Taiji pathfinder is designed to cover almost all the Taiji technologies except the time delay interferometer [35]. A schematic diagram of the mission design for the Taiji pathfinder is shown in Fig. 6.

Each spacecraft of Taiji pathfinder will have only one laser interferometer system, forming a single-arm laser interferometer space antenna. Since time delay interferometry cannot be applied, the noise budget will be dominated by laser frequency noise. The choice of arm length will be determined based on the performance of the arm-locking scheme [36]. One of the satellites will have two sets of inertial sensors which will be arranged in the same way as Taiji. Therefore, we can test the two degrees of freedom drag-free control method. To reduce the cost, there may be one inertial sensor on the other spacecraft.

Due to their extreme importance, some individual technologies, such as the laser interferometer, gravitational reference sensor, μN thruster, and drag-free control have been flight tested during the first stage. Taiji-1, regarded as the Taiji pre-pathfinder, aims to test the most important individual technologies, and was launched on August 31, 2019. The first-stage in-orbit test of Taiji-1 showed that the accuracy of the displacement measurement of the laser interferometer reached the 100 picometer order of magnitude, the accuracy of the gravitational reference sensor on the satellite reached sub-nano-g, and the resolution of the micro-thruster was better than 1 μN. The successful test shows that the Taiji-1 payloads work properly and the performance meets the expectation of the Taiji-1 mission design, which indicates that the Taiji technology roadmap is feasible.

6. Conclusions

The Taiji system design and key technology development are progressing steadily, and Taiji is now officially funded by the Chinese Academy of Sciences. The basic system design concept is now beginning to take shape. After a few iterations, and particularly with the invaluable experience of LISA collaboration, the Taiji program and Taiji pathfinder will soon be much more developed in engineering terms.

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References

[1] B. P. Abbott et al. [LIGO Scientific Collaboration and Virgo Collaboration], Phys. Rev. Lett. **116**, 061102 (2016).
[2] A. Abramovici et al., Science, **256**, 325 (1992).
[3] LISA Consortium, "LISA: Laser Interferometer Space Antenna: A proposal in response to the ESA call for L3 mission concepts" (available at https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf, date last accessed July 28, 2018).
[4] LISA Consortium, "LISA: Unveiling a hidden Universe" (ESA, Paris, 2011) (available at https://sci.esa.int/documents/35005/36499/1567258681608-LISA_YellowBook_ESA-SRE-2011-3_Feb2011.pdf, date last accessed May 24, 2020).
[5] X. Gong et al., Class. Quantum Grav. **28**, 094012 (2011).
[6] P. L. Bender, Class. Quantum Grav. **21**, S1203 (2004).
[7] S. Phinney, P. Bender, R. Buchman, R. Byer, N. Cornish, P. Fritschel, and S. Vitale, "The Big Bang Observer: Direct detection of gravitational waves from the birth of the Universe to the Present". NASA Mission Concept Study (2004).
[8] N. Seto, S. Kawamura, and T. Nakamura, Phys. Rev. Lett. **87**, 221103 (2001).
[9] Y. Wu, "Space Gravitational Wave Detection in China". Presentation to 1st eLISA Consortium Meeting, APC Paris, Oct. 22–23, 2012 (available at http://www.apc.univ-paris7.fr/APC/Conferences/First_eLISA_Consortium_Meeting/Expose_files/China_YLWU.ppt, date last accessed May 24, 2020).
[10] W.-H. Ruan, C. Liu, Z.-K. Guo, Y.-L. Wu, and R.-G. Cai, Nat. Astron. **4**, 108 (2020).
[11] Y.-Q. Li, Z.-R. Luo, H.-S. Liu, Y.-H. Dong, and G. Jin, Chin. Phys. Lett. **29**, 079501 (2012).
[12] H.-S. Liu, Y.-H. Dong, Y.-Q. Li, Z.-R. Luo, and G. Jin, Rev. Sci. Instrum. **85**, 024503 (2014).
[13] Y.-H. Dong, H.-S. Liu, Z.-R. Luo, Y.-Q. Li, and G. Jin, Rev. Sci. Instrum. **85**, 074501 (2014).
[14] Y.-q. Li, Z.-r. Luo, H.-s. Liu, Y.-h. Dong, and G. Jin, App. Phys. B **118**, 309 (2015).
[15] H. Liu, Y. Dong, Z. Luo, Y. Li, and G. Jin, Sci. China Technol. Sci. **58**, 746 (2015).
[16] Y. Dong, H. Liu, Z. Luo, Y. Li, and G. Jin, Sci. China Technol. Sci. **58**, 449 (2015).
[17] Y. Dong, H. Liu, Z. Luo, Y. Li, and G. Jin, Sci. China Technol. Sci. **59**, 730 (2016).
[18] X. Gong et al., J. Phys.: Conf. Ser. **610**, 012011 (2015).
[19] D. Cyranoski, Nature News **531**, 150 (2016).
[20] W.-R. Hu and Y.-L. Wu, Nat. Sci. Rev. **4**, 685 (2017).
[21] Z. Luo, Q. Wang, C. Mahrdt, A. Goerth, and G. Heinzel, Appl. Optics **56**, 1495 (2017).
[22] Z. Luo, H. Liu, and G. Jin, Optics & Laser Tech. **105**, 146 (2018).
[23] H. Liu, Z. Luo, and G. Jin, Micrograv. Sci. Technol. **30**, 775 (2018).
[24] H. Liu, Y. Dong, R. Gao, Z. Luo, and G. Jin, Optical Eng. **57**, 054113 (2018).
[25] W. Deng, T. Yang, J. Cao, E. Zang, L. Li, L. Chen, and Z. Fang, Optics Lett. **43**, 1562 (2018).
[26] Z. Wang, W. Sha, Z. Chen, Y. Kang, Z. Luo, M. Li, and Y. Li, Chinese Optics **11**, 131 (2018) (in Chinese).

[27] O. Jennrich, et al., "NGO assessment study report (yellow book)," ESA/SRE(2011)19 (ESA, Paris, 2012) (available at https://sci.esa.int/documents/34985/36280/1567258287202-NGO_YB.pdf, date last accessed May 24, 2020).
[28] P. Madau and M. J. Rees, Astrophys. J. **551**, L27 (2001).
[29] X.-f. Gong et al., Chin. Astron. Astrophys. **39**, 411 (2015).
[30] L. Barack and C. Cutler, Phys. Rev. D **75**, 042003 (2007).
[31] W.-B. Han and X.-L. Fan, Astrophys. J. **856**, 82 (2018).
[32] J. D. Romano and N. J. Cornish, Living Rev. Rel. **20**, 2 (2017).
[33] Y.-L. Wu, Phys. Rev. D **93**, 024012 (2016).
[34] M. Armano et al., Phys. Rev. Lett. **116**, 231101 (2016).
[35] M. Tinto, and S. V. Dhurandhar, Living Rev. Rel. **8**, 4 (2005).
[36] B. S. Sheard, M. B. Gray, D. E. McClelland, and D. A. Shaddock, Phys. Lett. A **320**, 9 (2003).