The TianQin project

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In this talk, I give a brief introduction to the TianQin project, which aims to start space-based gravitational wave detection in the 2030s. My main focus will be on the background, the preliminary concept, the scientific objectives, the development of key technologies, the current progress and the international collaboration of the project.

Keywords: TianQin; Gravitational waves; Space-based gravitational wave detection.

1. Introduction

Discussions leading to the TianQin project started in 2013 when a team of scientists from the Sternberg Astronomical Institute, Moscow State University, joined our team at the Huazhong University of Science and Technology (HUST) to discuss ideas for future gravitational experiments in space. The focus of the discussion gradually shifted to a feasible gravitational wave mission in space from China. The name "TianQin" was proposed during a meeting in March 2014, followed by the first international workshop on the TianQin science mission in December 2014. A systematic development of the TianQin project was initiated in Sun Yat-sen University (SYSU) in early 2015. The paper summarizing the preliminary mission concept of TianQin was submitted to *Class. Quant. Grav.* on September 1, 2015[1], 13 days before LIGO detected its first gravitational wave signal.

The name of the planned detector (which will be consisted of three satellites), TianQin, is the phonetic spelling of two Chinese characters that, when put together, mean a harp in space. By choosing this name, the detector is metaphorically seen as a musical instrument in space to be played by nature with gravitational waves.

In this talk, I shall give a brief introduction to the TianQin project, including the background (section 2), the preliminary concept (section 3), the scientific objectives (section 4), the development of key technologies (section 5), the current progress (section 6) and the international collaboration (section 7) of the project.

2. Background

For more than 100 years, General Relativity has passed numerous non-trivial experimental tests, including[2]:

- orbital precession of mercury,
- deflection of light by sun,

- gravitational redshift,
- Shapiro delay,
- frame dragging,
- gravitational lensing,

and so on. The first detection of gravitational waves by LIGO in 2015[3] opened a new era when General Relativity can be tested under extreme conditions where even black holes can be radically deformed.

Gravitational waves are extremely weak. In the first event detected by LIGO, GW150914, two black holes with masses $29M_\odot$ and $36M_\odot$ merged at about 1.3 billion light years away[3], producing gravitational waves with strength at the order 10^{-21} when reaching Earth. The effect of such gravitational wave is comparable to deforming the distance between the Sun and the Earth by the size of an atom! For this reason, it has taken people a whole century to detect gravitational waves after its prediction by Einstein in 1916.

Gravitational waves provide a new method to study the universe, providing crucial information on the origin and growth of stars, galaxies and the Universe itself, and on the nature of gravity and black holes. New discoveries have already been made with the few gravitational wave events detected since 2015, including:

- Showing that massive stellar mass black holes are more abundant than expected[4];
- Demonstrating the feasibility of multi-messenger astronomy[5,6];
- Showing that binary neutron star mergers are cosmic factories of heavy elements and are central engines of short gamma ray bursts[7].

Close to the frequency band of about $10\text{Hz}\sim 10^4\text{Hz}$ that has already been opened up with ground based detectors, the millihertz (mHz) frequency band (which typically corresponds to the frequency range $10^{-4}\text{Hz}\sim 1\text{Hz}$) also has many types of important astronomical and cosmological sources:

- Galactic compact binaries can produce gravitational waves with periods in the order of a few minutes;
- Systems involving massive black holes can produce gravitational waves with periods from minutes to years;
- The birth and the initial expansion of the Universe may leave detectable gravitational waves at all frequencies.

To detect gravitational waves in the mHz frequency band, we need a laser interferometer with arm lengths at the order 10^5km or greater and to stay away from the seismic noise that has become a limiting factor below about 10Hz for ground based detectors. So the only feasible way is to put the detector in space.

The idea of using a laser interferometer in space to detect gravitational waves can be traced back to the 1970s, and the first such mission concept LAGOS was proposed in the 1980s[9]. By far the most studied mission concept for space-based gravitational wave detection is LISA, which envisages three spacecraft forming a regular triangle with each side measuring about 2.5 million kilometers[10]. LISA has been selected as the L3 mission in the Cosmic Vision 2015-2025 programme of ESA and is expected to launch in 2034[11].

When TianQin was first proposed in 2014, it was more intended to be an experiment rather than an observatory, with the main goal to verify the prediction of gravitational waves by General Relativity[1]. After the first detection of gravitational waves by LIGO, this primitive goal of TianQin has to be updated. Thanks to the fact that all laser interferometer-based gravitational wave detectors are wide band detectors, TianQin has the natural capability of being a space-based gravitational wave observatory. However, the initial goal of TianQin has allowed it to take some special features that are not shared by any other mission concept proposed. One of our task is to investigate the consequence of such special features when TianQin is to be treated as a gravitational wave observatory.

3. The preliminary concept of TianQin

A description of the mission concept of TianQin has been presented in[1]. Here I only summarize some of the key features:

- TianQin will be consisted of three satellites, forming a regular triangle constellation;
- The TianQin satellites will be on nearly identical geocentric orbits with radii at the order 10^5 kilometers;
- The plane of the TianQin constellation is nearly perpendicular to the ecliptic (the original reason was to let the plane face the ultra-compact binary system RX J0806.3+1527, so as to maximize the response of TianQin to this particular source).

The adoption of geocentric orbits brings some advantages for TianQin: the transfer time for the TianQin satellites to enter the scientific operation orbits is at the order of dozens of days and TianQin foresees little difficulty with communicating with Earth.

However, the same geocentric orbits also bring some extra challenges.

Firstly, TianQin is facing a complicated celestial dynamical environment for being close to Earth and Moon, which directly leads to the question that if TianQin can even find such orbits that are suitable for gravitational wave detection. For TianQin, a candidate orbit need to satisfy the following constraints in order not to interfere with gravitational wave detection:

- The distance between any two satellites need to be very stable, e.g. varying less than 1% throughout the mission lifetime;
- The relative velocity between any two satellites need to be small, e.g. being less than 10m/s during scientific observation time;

- The angle between any pair of arms of the constellation need to be stable, e.g. varying no more than 0.1 degree in the short term (several months) and no more than 0.2 degree in the long term (years).

It has been shown that an orbit satisfying all the above requirement does exist[1].

Recent study has produced more candidate orbits with different orientations, for which all the above constraints are satisfied[12]. Knowledge of the orbit is important for data analysis purpose. An analytical approximation has also been obtained for the orbits of the TianQin satellites, based on which the response of TianQin to gravitational waves have been calculated[13]. The response allows us to expedite the procedure of simulating the stain data output of the detector with decent accuracy and conduct subsequent investigations on the data analysis techniques for various sources.

Secondly, all the orbits known for geocentric gravitational wave mission have their orientation nearly fixed in space. This can be seen in the many examples studied in[14]. As a result, the telescopes used for inter-satellite laser ranging will periodically point toward the Sun. Varying solar radiation on the telescopes can lead to temperature fluctuation and temperature gradient in the satellites, causing problem for the detection of gravitational waves.

With TianQin, a solution to this problem is made possible by a particular feature of the mission: the “standing” orbital plane. The plane of the TianQin constellation is facing J0806, and the location of the latter is about 4.7° below the ecliptic. As a result, the plane of the TianQin constellation is nearly perpendicular to the ecliptic and it will sweep through Sun only twice a year.

When the plane of the TianQin constellation comes too close to the Sun, there will be times that the telescopes point too close to the direction of the Sun, causing problems for the observation. TianQin adopts a “3-month on + 3-month off” detection scheme (to be further optimized) to cope with the problem. The orbit of the Earth can be partitioned into four sections, each has about 3 months:

- From early June to early September and from early December to early March, sunlight is at large angles with respect to the plane of the TianQin constellation. During such times, the telescopes will be well protected from the Sunlight.
- From early March to early June and from early September to early December, sunlight is at small angles with respect to the plane of the TianQin constellation. During such times, there can be direct sunshine on the telescopes and TianQin will suspend observation.

As such, TianQin solves the problem but pays the price of having shortened observation time.

4. The scientific objectives of TianQin

The main gravitational wave sources for TianQin include Galactic compact binaries, massive black hole binary coalescence, extreme mass ratio inspirals, stellar mass black hole inspirals, possible first order phase transition in the early Universe, and possibly some unforeseen sources[8]:

- With Galactic compact binaries, TianQin seeks to study the formation and evolution of compact Galactic binaries, to combine GW+EM observation to obtain comprehensive understanding of the Galactic binary systems.
- With massive black hole binary coalescence, TianQin seeks to discover seed black holes in the early universe, to depict massive black hole growth process, to study the surrounding environment of massive black hole merger, to test the Kerr-ness of the post-merger object, and to test deviation from General Relativity.
- With extreme mass ratio inspirals, TianQin seeks to study the dynamic environment around black holes in the nearby universe, to explore the fundamental nature of gravity and black holes, including: the multipolar structure and Kerr-ness of the central massive object, the beyond-general relativity emission channels, the propagation properties of gravitational waves, and the presence of massive fields around massive black holes.
- With stellar mass black hole inspirals, TianQin seeks to facilitate multi-band and multi-messenger observation, and to enhance parameter estimation accuracy, to provide better understanding of the system as well as the nature of gravity.
- With the waveform of a binary system, TianQin seeks to constrain the parameters that characterize the deviation of modified theories of gravity from general relativity.
- TianQin seeks to detect stochastic gravitational waves background originated from stellar mass black hole mergers or even binary neutron star mergers, and to measure or set limit on cosmic origin stochastic background (e.g., first order phase transitions).

We also expect enhanced science output if there is enough overlap in the operation times of TianQin and LISA[15,16].

5. The development of key technologies and research teams

TianQin will rely on high precision intersatellite laser interferometry to detect gravitational waves. Two test masses will be placed inside each of the three TianQin satellites. These test masses will be used as the end points for laser interferometry between the satellites. The ideal situation is that the test masses exactly follow the geodesics determined by the ambient gravitational field. In reality, however, there is environmental effect on the test masses due to electromagnetic force, particle collision and so on. So the variation of distance between the test masses and the satellite is closely monitored and the information is used to control the satellite to follow the motion of the test masses. For this process to work, one will need high precision inertial sensors, micro-Newton thrusters and a dragfree control mechanism.

For the inertial sensor, a preliminary conceptual design for TianQin has been presented in[1]. TianQin requires that the resolution of the inertial sensor is at the order $10^{-15}\mathrm{m/s^2/Hz^{1/2}}$ in the mHz frequency band.

Our team has started working on inertial sensors since 2000. A space electrostatic accelerometer with a resolution of $4 \times 10^{-8}\mathrm{m/s^2/Hz^{1/2}}$ and a dynamic range of 10^{-2} $\mathrm{m/s^2}$ is being tested and functions well in flight from Nov. 2013 up to now[18]. A second space electrostatic accelerometer with a resolution of 3×10^{-10} $\mathrm{m/s^2/Hz^{1/2}}$ and a dynamic range of $10^{-5}\mathrm{m/s^2}$ has been put to use in space from April to Sep. 2017[19].

For intersatellite laser interferometry, TianQin requires that the displacement measurement noise is at the order $10^{-12}\mathrm{m/Hz^{1/2}}$ in the mHz frequency band. In order to achieve this level of accuracy, we need technologies with laser interferometer (including ultra-stable optical bench, laser, telescopes, and clocks and so on), and ultra-stable temperature control of the satellite platform. A preliminary conceptual design for the space laser interferometry for TianQin has been given in[1].

Our team has started working on intersatellite laser interferometry since 2002. We have built a 10-m prototype of intersatellite laser ranging system in 2010 and a resolution of 3.2 nm has been achieved[20]. An ultra-precise phasemeter has been developed in 2012 and a noise level of $1.2\mu\mathrm{rad/Hz^{1/2}}$ at 1Hz has been achieved[21]. Recently, a novel scheme of intersatellite laser beam acquisition has been developed. The averaged acquisition time is 10 s for a scanning radius of 1 mrad with a success rate of 99%[22].

Apart from that for the key payloads, satellite technology is needed to provide ultra-stable and clean environment for the scientific payload and to form and maintain a highly coordinated constellation throughout the scientific observation period. A team responsible for the satellite/system technology has been assembled in SYSU to study the problems in this direction.

A team responsible for theoretical and data analysis has also been assembled in SYSU.

Apart from the teams at HUST and SYSU, there are many other groups in China that have technology background related to space-based gravitational wave detection. There is an effort to engage all these teams in the work of TianQin.

6. Recent progress

In order to support the development of key technologies, we are constructing a few dedicated research facilities and have started flight experiments on TianQin key technologies.

6.1. *Dedicated research facilities*

As of present we are constructing three dedicated TianQin research facilities:

- The Payload Research Base, which is responsible for all key technology research and development for the project.
- A laser ranging station, which will be used to develop laser ranging capability to TianQin satellites.
- The Ground Simulation Facility, which is responsible for integrated test and research on the TianQin technologies and prototypes.

The Payload Research Base is consisted of the TianQin Research Building and a cave lab. The TianQin Research Building has about 30 thousand square meters in total area and the cave lab has about 10 thousand square meters in total area. The construction of the Payload Research Base and the laser ranging station has started on the SYSU Zhuhai campus in the end of 2017. The TianQin Research Building will be delivered by the end of 2019. The tunnel of the cave lab will be finished by the end of 2020.

The laser ranging station will be equipped with a 1.2 meter telescope, plus an education and outreach facility. The laser ranging station will be ready in the early part of 2019.

The Ground Simulation Facility is a big effort in the TianQin project. The idea is to have a facility that can simulate as close as possible the various aspects of a space-based gravitational wave mission. The facility will have the capability to simulate space environment, inertial reference, inter-satellite laser interferometry, the formation of TianQin constellation and the process of space-based gravitational wave observation. The facility will also aid in signal abstraction and data analysis. The facility will be located on the SYSU Shenzhen Campus.

6.2. *Flight experiments*

There are two space experiment projets going on at the moment:

- Laser ranging to the Chang'E 4 (CE4) relay satellite;
- The TQ-1 experimental satellite.

Laser ranging technology will be used to help tracking the TianQin satellites. In order to bring the needed technology to mature, the TianQin project has planned a lunar laser ranging program, which involves (1) creating new generation corner cube retro-reflectors to be deployed on the surface of Moon or to be carried by high Earth orbit satellites, and (2) upgrading/constructing laser ranging stations on the ground. The CE4 relay satellite (QueQiao) has been launched on May 21, 2018 and has successfully entered a Lissajous orbit around the Earth-Moon L2 point. Our team have created a single large aperture hollow corner cube retro-reflector (CCR) and have installed it on the QueQiao satellite. Our next step is to do laser ranging experiment to the CCR onboard the QueQiao satellite. As part of the project, the Yunnan Observatory (located in Kunmin, China) has successfully carried out the first lunar laser rang experiment in China early 2018. A new laser ranging station is also being constructed on the SYSU Zhuhai campus and is expected to become available in the spring of 2019.

We are also preparing for the first experimental satellite, TQ-1, on TianQin key technologies. The satellite will be equipped with an inertial sensor reaching the resolution level $10^{-12}\text{m/s}^2/\text{Hz}^{1/2}$ at 0.1Hz, a laser interferometer reaching the resolution level $0.1\text{nm/Hz}^{1/2}$ at 0.1Hz. The mission has been approved by the China National Space Administration and is scheduled for launch in late 2019.

7. International collaboration

International collaboration is an important aspect of the TianQin project. The effort on the TianQin project is expected to span some 15 years. Due to the long duration of the effort, a core team is necessary to make sure that the project evolves as expected. Currently the core team of TianQin is consisted of two teams, located in two universities in China, Huazhong University of Science and Technology (HUST) and Sun Yat-sen University (SYSU). The team at HUST was formed in 1983 and has grown to more than 300 researchers and students by now. SYSU has established in 2016 a new center dedicated to the TianQin project, the TianQin Research Center for Gravitational Physics. The center has grown to more than 100 researchers and students by now.

The TianQin collaboration has been formally established in the end of 2018 during the fifth international workshop on the TianQin science mission.

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