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Progress Toward a Space-Based Gravitational Wave Observatory

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Abstract. The discovery of binary pulsar PSR 1913+16 by Hulse & Taylor in 1974 established the existence of gravitational waves, for which the 1983 Nobel Prize was awarded. However, the measurement of astrophysical parameters from gravitational waves will open an entirely new spectrum for discovery and understanding of the Universe, not simply a new window in the electromagnetic spectrum like gamma ray telescopes in the 1970s. Two types of ground-based detectors, Advanced LIGO/Virgo and Pulsar Timing Arrays, are expected to directly detect gravitational waves in their respective frequency bands before the end of the decade. However, many of the most exciting sources are in the band from 0.1–100 mHz, accessible only from space due to seismic and gravity gradient noise on Earth. The European Space Agency (ESA) has chosen the 'Gravitational Universe' as the science theme for its L3 Cosmic Visions opportunity, planned for launch in 2034. NASA is planning to participate as a junior partner. Here we summarize progress toward realizing a gravitational wave observatory in space.

Keywords. gravitational waves, instrumentation: interferometers

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1. Introduction: Why a Space-based Observatory is Important

The 0.1 mHz to 1 Hz frequency band is expected to have a large number of strong and persistent astrophysical sources of gravitational waves (Schutz 1999), but it is not accessible with ground-based detectors due to fluctuations in the local gravitational field caused by changes in the local mass distribution at those frequencies. The LISA mission (Bender *et al.* 1998), a joint NASA-ESA project, has been the reference mission for observing this band from space for nearly 30 years. A LISA-like mission has five essential elements: (1) drag free test masses that are shielded from extraneous forces and free to move inertially within the measurement bandwidth, (2) continuous laser ranging between pairs of test masses, (3) test mass separations of order a million kilometers, (4) heliocentric orbits for a stable environment, and (5) laser frequency noise subtraction (Time Delay Interferometry).

Budget constraints have forced reformulation of the basic mission concept at both NASA and ESA to achieve a lower cost point, although with a loss of science. The basic elements of a LISA-like mission force a cost point of ∼\$1B (Anderson *et al.* 2012, Table 19) in order to achieve the science return beyond a simple detection. Since we expect a direct detection by ground-based laser-interferometric observatories like Advanced LIGO and Virgo and by pulsar timing arrays such as NANOGrav before a space-based mission launches, a simple detection is not sufficiently compelling and a real observatory-class mission is required. An observatory would not only detect (i.e., count) sources but be capable of extracting details (parameter estimation) of the astrophysical systems. Figure 1 summarizes the science return expected across the gravitational wave spectrum, showing the different astrophysical sources as a function of frequency. Different frequency bands cover different and complementary types of sources, but the band accessible from

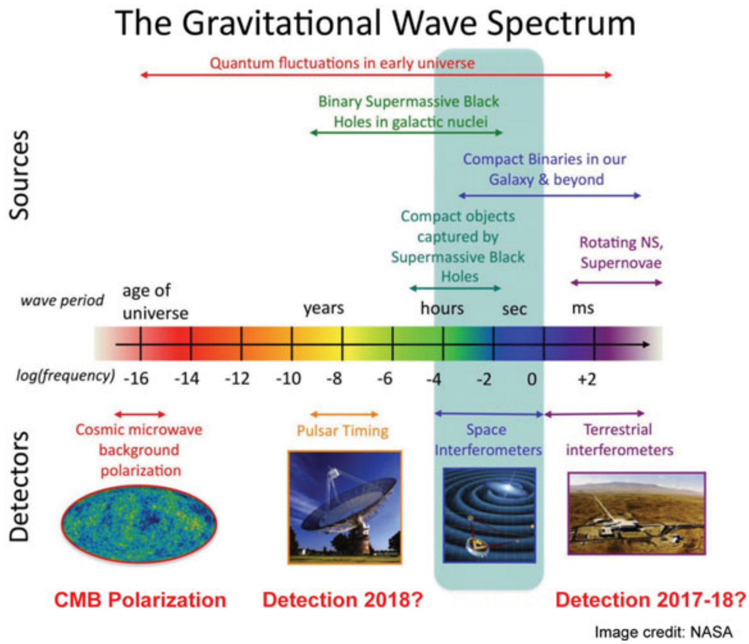

Figure 1. Gravitational wave spectrum showing expected sources in different frequency bands. The millihertz band, accessible only from space, is very rich in expected sources.

space has a rich population of continuous sources. Many of the galactic compact binaries are already known from electromagnetic observations, and should be observable immediately after the space-based observatory becomes operational. This is in contrast to ground-based interferometers that must wait for transient events, such as mergers or supernovae, to occur.

This paper briefly reviews the status in both the U.S. and Europe and the progress toward a space-based gravitational wave observatory.

2. Global Activity and Possible Timeline

The "Gravitational Universe" has been selected as the science theme for the L3 mission opportunity of ESA's Cosmic Visions Program, with a nominal launch date of 2034. The call for the selection of a specific mission concept is expected to be issued mid-to-late 2016, shortly after the results of the technology demonstration LISA Pathfinder mission are known. Three of the most likely proposed mission concepts are discussed in the next section, but it is expected that the mission will be based on a LISA-like laser interferometer design.

Figure 2 shows a notional timeline of activities at ESA, NASA, and elsewhere, leading up to an L3 mission. The middle of Figure 2 shows the technology development activity in the U.S for space-based gravitational wave detectors, with the specific goal of delivering technologies at the TRL 5/6 level for inclusion in the Engineering Model (EM) development activity scheduled for the beginning in 2019. The EM activity is part of a nominal schedule developed for ESA's Gravitational Observatory Advisory Team (GOAT)† to illustrate one possible mission timeline. A summary of this schedule is shown in the upper third of Figure 2. Key milestones include the adoption of a mission concept by the ESA

† `http://www.cosmos.esa.int/web/goat`

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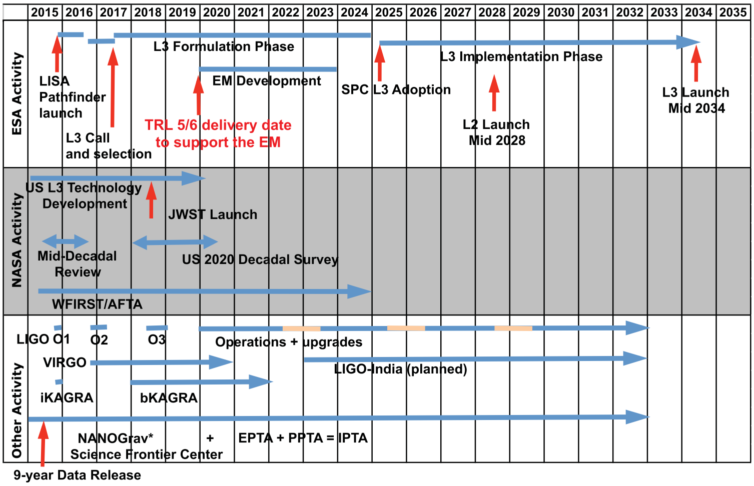

Figure 2. One possible timeline showing activities for the development of a space-based gravitational wave observatory as the L3 launch opportunity in ESA's Cosmic Visions Programme. In parallel, technology development proceeding in the U.S., and globally there is activity in the ground-based interferometer networks and pulsar timing arrays.

Scientific Program Committee (SPC) at the beginning of 2025, and a nominal launch date of 2034.

Currently there is much activity and excitement in the ground-based gravitational wave detector community as the Advanced LIGO detectors in Hanford, Washington and Livingston, Louisiana complete the first planned science run at the end of 2015. The science run will be followed by improvements to the detectors, and then another science run in 2016. This alternating pattern of science runs punctuated by improvements to the detector is expected to continue until the detectors achieve design sensitivity. The Japanese KAGRA detector will complete an initial science run by the end of this year, and then join the ground-based network at the beginning of 2018. The Italian-based Virgo detector is scheduled to join the network at the end of 2016, and a detector in India is planned for operations beginning in 2022. An approximate timeline for these activities is shown in the lower third of Figure 2. The ground-based interferometers will detect primarily transient events such as the endpoint of neutron star-neutron star binary mergers, and will also enable multi-messenger operations with other electromagnetic observatories, both space- and ground-based, through a program of alerts. Pulsar timing arrays are expected to observe a stochastic gravitational-wave background from supermassive black hole binary mergers at nanohertz frequencies. Both of these activities will probe very different types of astrophysical sources as indicated in Figure 1. We expect that discoveries and activity in these bands will raise awareness of gravitational waves and the complementary nature of these observations with electromagnetic observations, and not diminish the attraction of a space-based observatory.

3. Comparison of Proposed Missions

The original LISA mission design remains the baseline reference mission against which all other missions are compared. Figure 3 shows a comparison between the main mission parameters of the baseline LISA reference mission, the mission currently proposed for the L3 Cosmic Visions opportunity, Next Gravitational-wave Observatory (NGO), and

Parameter	NGO	SGO Mid	LISA
Measurement arm length	1 x 10^6 km	1 x 10^6 km	5 x 10^6 km
Number & type of spacecraft	1 corner (2 optical assemblies, 2 end (single optical assembly	3 corner (2 optical assemblies)	3 corner (2 optical assemblies)
Number of measurement arms, one-way links	2 arms, 4 links	3 arms, 6 links	3 arms, 6 links
Constellation	Vee	Triangle	Triangle
Gravitational-wave polarization measurement	Single instantaneous polarization, second polarization by orbital evolution	Two simultaneous polarizations continuously	Two simultaneous polarizations continuously
Orbit	Heliocentric, earth-trailing, drifting-away 9°- 21°	Heliocentric, earth-trailing, drifting-away 9°- 21°	22° heliocentric, earth-trailing
Trajectory	Launch to Geosynchronous Transfer Orbit, transfer to escape, 14 months	Direct injection to escape, 18 months	Direct injection to escape, 14 months
Duration of science observations	2 years	2 years	5 years
Launch vehicle	Two Soyuz-Fregat	Single Medium EELV (e.g., Falcon 9 Block 3)	Single Medium EELV (e.g., Atlas V 551)
Optical bench	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction
Laser	2 W, 1064 nm, frequency and power stabilized	1 W, 1064 nm, frequency and power stabilized	2 W, 1064 nm, frequency and power stabilized
Telescope	20 cm diameter, off-axis	25 cm diameter, on-axis	40 cm diameter, on-axis
Gravitational Reference Sensor	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout

Figure 3. Comparison of the main mission parameters among the LISA reference mission, NGO, and SGO-Mid.

a NASA-developed mission concept SGO-Mid that is a scaled-down version of the LISA baseline design. The main differences among the missions are the number of arms, the length of the arms, and the duration of the mission. Note that the most cost-effective way to increase the science return per dollar is simply to extend the lifetime of the mission, since once the observatory is launched, funding is needed only to keep ground operations continuing.

Proposed mission concepts for a space-based gravitational wave mission respond to the science recommendations of ESA and NASA advisory bodies that encompass substantial astrophysics and fundamental physics results. The mission will study gravitational wave sources and extract the parameters of those sources that are of astrophysical interest. Figure 4 shows the expected science return from each of the missions described in Figure 3. That science return is gauged by both the numbers of sources and how well the astrophysical parameters of those sources are determined for a grid of cosmological models.

A very important consideration for best science return is to fly a mission with a complete triangle of 3 arms/6 links. Initial cost estimates indicated that reducing the design to 2 arms from 3 would lower the cost, but a more careful estimate shows that the cost actually may increase slightly as we lose part of the discount associated with identical parts, and the loss of science is large because instantaneous polarization information essential for extracting estimates of the parameters is no longer available. Three arms enable the detector to be operated in a Sagnac mode which can be used to simultaneously monitor the instrument noise. This mode is particularly important for characterizing stochastic backgrounds. Therefore the LISA baseline and SGO-Mid designs are preferred over the NGO concept. More information on these and other concepts is available in the final report of a study of mission concepts conducted in 2012 (GW Study 2012).

Figure 4 shows that the loss of science is dramatic for two arms, and the difference between the SGO-Mid three-arm mission and the LISA Baseline is also dramatic. Part of the loss of science is simply due to the shorter mission, but the polarization information and longer arm lengths also are important for the precision and quality of the parameter estimation. Accurate parameters are essential to enable observations to distinguish

	NGO	SGO Mid	LISA
Massive Black Hole Binary Totals	40-47	41-52	108-220
Detected z > 10	1-3	1-4	3-57
Both mass errors < 1%	13-30	18-42	67-171
One spin error < 1%	3-10	11-27	49-130
Both spin errors < 1%	<1	<1	1-17
Distance error < 3%	3-5	12-22	81-108
Sky location < 1 deg^2	1-3	14-21	71-112
Sky location < 0.1 deg^2	<1	4-8	22-51
Extreme Mass-Ratio Inspirals	12	35	800
Resolved Compact WD Binariess	3,889	7,000	40,000
Interacting	50	100	1,300
Detached	5,000	8,000	40,000
Sky location < 1 deg^2	1,053	2,000	13,000
Sky location < 1 deg^2, distance error < 10%	533	800	8,000
Stochastic Background (normalized)	0	0.2	1

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Figure 4. Comparison of the science return among the missions described in Figure 3. The ranges given reflect the anticipated variation in science return for different cosmological models (e.g., size of massive black hole progenitors or role of accretion in mass growth.

between different underlying models for the different classes of sources. As a rough metric, the difference in estimated cost between the reference LISA mission and the SGO-Mid proposal is approximately 10%, and the loss in science ranges from a factor of 3 to more than 20. Thus the full baseline LISA mission remains the best overall science return per unit cost.

4. Near Term Acitivity: LISA Pathfinder

In a much anticipated event, ESA's LISA Pathfinder mission is scheduled for launch in early December 2015 from the ESA spaceport in Kourou, French Guiana. The LISA Pathfinder mission will demonstrate the test mass technology that is an essential part of the measurement system for all LISA-like mission concepts. The mission's main purpose will be to verify the noise budget for the test mass. U.S. hardware contributions to the mission are collectively referred to as ST7, and include micro-newton colloidal thrusters, and control laws. Figure 5 shows the completed LISA Pathfinder spacecraft mated to its propulsion module and launch adapter being unloaded at the launch site.

NASA activities in support of the L3 Cosmic Visions Opportunities include participation in the LPF and ST7 missions, developing technology to meet the development schedule adopted by the GOAT, and direct participation on the GOAT. In addition, NASA is preparing to seek an endorsement for L3 participation from the 2020 Astronomy & Astrophysics Decadal Review.

5. Summary

ESA has selected a gravitational wave mission for its L3 opportunity. The mission concept will be selected in late 2016 or early 2017, but is likely to be a LISA-like design. This choice takes advantage of years of study and formulation work both at NASA and ESA, and the substantial investment in the LISA Pathfinder technology demonstration mission, poised to launch in December 2015. NASA's Astrophysics strategic plan calls for NASA to seek a minority role in L3. To that end, NASA is: (1) participating in

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Figure 5. The full integrated LISA Pathfinder Spacecraft, propulsion module, and launch adapter being unloaded at the launch site in Kourou, French Guiana.

LISA Pathfinder and ST7, (2) developing appropriate technology for a LISA-like mission, (3) negotiating with ESA for a role in L3, and (4) preparing to seek an endorsement for that role from the 2020 decadal review in astrophysics.

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