LISA AND THE GRAVITATIONAL WAVE UNIVERSE

BERNARD F. SCHUTZ
Max Planck Institute for Gravitational Physics
(Albert Einstein Institute)
Am Mühlenberg 1
14476 Golm, Germany
and
Department of Physics and Astronomy
Cardiff University
Cardiff, UK
Email: schutz@aei.mpg.de

FOR THE LISA INTERNATIONAL SCIENCE TEAM

The ESA–NASA joint mission LISA will open the gravitational-wave window to low frequencies, between roughly 0.1 mHz and 0.1 Hz. Sources of radiation at these frequencies are very different from those that the ground-based detectors are expecting to see. LISA can uncover the history of the formation of the giant black holes in galactic centers; it will explore the compact binary population of our Galaxy; it will test general relativity and its description of black holes with unprecedented accuracy; and it has a good chance of revealing a background of gravitational radiation created in the Big Bang. In this lecture I will review these sources of gravitational waves and set them in the context of the physics of gravitational-wave sources and the design of the LISA mission.

1. Introduction

1.1. *The gravitational wave spectrum*

The accessible gravitational-wave spectrum is illustrated schematically in Fig. 1. The horizontal frequency scale in the diagram runs from about 0.1 mHz to 10 kHz. The vertical scale is the gravitational wave amplitude, which is given as the dimensionless strain produced by the gravitational wave. The curves show roughly the detection limits expected of LISA[1] and of the advanced version of the ground-based detector LIGO[2]. The range spans as many decades of frequency as there are between X-ray detectors and radio telescopes.

A wave with an amplitude h will produce a change δL in the length L of

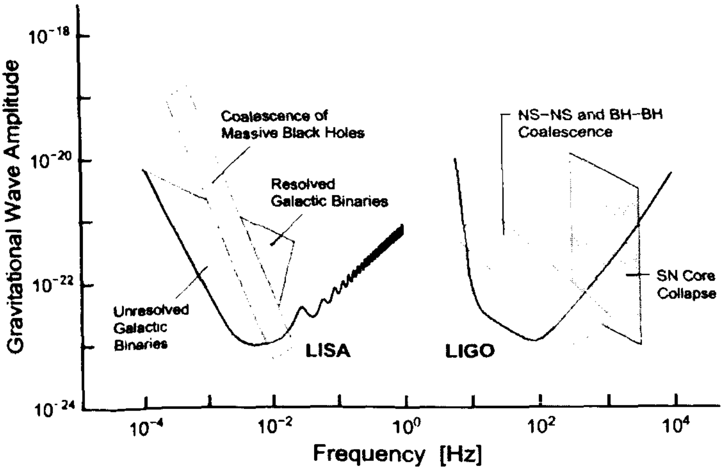

Figure 1. The gravitational wave spectrum from 0.1 mHz to 10 kHz. Sources are indicated schematically, as is the relative sensitivity of LISA and the ground-based LIGO detector.

an interferometer of size $\delta L = hL$. A wave with a fairly large amplitude of 10^{-21} will therefore change the length of LISA's 3×10^6 km arms by 3 pm. This is large compared to the changes expected in LIGO, whose 4 km arms will change by only 4×10^{-18} m, less than the diameter of a proton.

LIGO and LISA cover very different parts of the spectrum. LIGO will observe in the high-frequency band above about 10 Hz, while LISA will explore the low-frequency band between 0.1 mHz and about 0.1 Hz. Notice that there is a gap between their bands: no detector yet planned will open the intermediate band from 0.1 to 10 Hz. In the next section we will discuss the distinguishing properties of sources in these bands.

The LIGO sensitivity limit is set by instrumental effects, such as thermal noise in its mirrors. However, if we were to try to extend LIGO's observing bandwidth much lower, we would run into an environmental noise: temporal changes in the Newtonian gravitational field near LIGO due to changes in air density, density oscillations due to seismic waves, movements of people near the detector, and so on. These near-zone effects cannot be screened, and they are stronger than expected amplitudes of true gravitational waves from astronomical sources below about 1 Hz. This so-called *gravity-gradient wall* is the reason that LISA is designed as a space project.

1.2. *Physics across the gravitational wave spectrum*

Any body whose structure is determined by its own gravitational field has, in Newtonian gravity as well as in general relativity, a fundamental frequency of oscillation of the order of $f = (G\rho/4\pi)^{1/2}$, depending only on its mean density ρ. This leads to a simple relation among f and a body's mass M and typical size R: $f^2 \propto MR^{-3}$. Although bodies can oscillate at higher frequencies (overtones), one would expect that the dominant gravitational radiation would come out at the fundamental frequency except in special circumstances.

Now, since any body of mass M has a lower limit on R given by its gravitational radius $2GM/c^2$, there is an upper limit on the fundamental frequency determined by its mass. It turns out that this limit is about 1 Hz when $M \sim 10^4 M_\odot$[3]. Therefore sources in the high-frequency band should be of low mass, under $1000M_\odot$. LIGO and the other ground-based detectors (GEO600, VIRGO, TAMA, ...) will be looking for stellar sources, such as neutron stars and stellar-mass black holes. The strongest waves will come from catastrophic events involving these objects, such as their formation in supernova explosions or their destruction in binary mergers.

The supermassive black holes (SMBH) that inhabit galactic cores will emit at lower frequencies. LISA will be able to see events involving such holes up to masses of 10^7–$10^8 M_\odot$. These could be modest disturbances, such as when smaller black holes or neutron stars fall into such holes, or gigantic events, such as the coalescence of two such holes from a binary orbit.

Also in the LISA waveband are systems containing compact objects but where the mean density of the system is low, such as binary systems of white dwarfs, neutron stars, and black holes. If the binary orbital period is shorter than a few hours, these systems will be visible to LISA.

1.3. *Summary of LISA's sources*

The amplitude of a gravitational wave near its source is never more than the *square* of its dimensionless Newtonian gravitational potential GM/Rc^2, and it falls off as $1/r$ as it moves further away[3]. If only a fraction ϵ of the mass of the system participates in emitting the radiation, then the amplitude decreases in proportion. From this it is easy to see that a binary merger of two $10^6 M_\odot$ black holes in a galaxy at a redshift of 1 will produce a wave whose amplitude is equal to or smaller than 10^{-17}, while the waves from a $10M_\odot$ black hole falling into a $10^6 M_\odot$ hole at a distance of 1 Mpc would be only 5×10^{-22}. LISA could therefore see supermassive binary mergers anywhere in the Universe, but captures of smaller black holes could be seen only in our near cosmological neighborhood.

A binary system consisting of two $0.5M_{\odot}$ white dwarfs with an orbital radius of 10^5 km at a distance of 1 kpc would radiate with an amplitude of about 10^{-21}. LISA would therefore be able to see all such systems in the Galaxy.

LISA's high sensitivity raises problems that LIGO and its partners will not face: confusion-limited backgrounds of gravitational wave events. Gravitational captures occur frequently enough and last long enough (months or years in LISA's waveband) that more distant events will blend together and form a noise background that will limit LISA's sensitivity to the nearest ones. And at frequencies below 1 mHz, the number of white-dwarf binaries in the Galaxy will be so large that they will have overlapping frequencies, and will again form a background that makes detecting the nearest ones difficult.

1.4. *Principles of observing gravitational waves*

Gravitational wave observation is unlike most other kinds of astronomical observing. In most of astronomy one collects photons: the observations are bolometric or flux-based. Gravitational wave detectors, by contrast, follow the oscillations of the waves directly: they are coherent amplitude detectors.

This leads to several important differences that affect how information will be extracted from observations:

- Spectroscopy and polarimetry are automatic. The detectors are linearly polarized, so a network of them returns complete polarization information. Since detectors measure the time-dependent phase of the wave, a simple Fourier transform produces a spectrum. Instruments can have spectral resolution over wide bandwidths (three decades or more).
- Simple "detection" usually measures parameters, e.g. of masses, orientations, and positions. The phase evolution of the wave depends sensitively on such parameters, and if this can be interpreted then it contains much information.
- Data analysis (computer-based) plays a key role in improving the sensitivity of a detector. The optimal analysis method is matched filtering, which requires a prediction of the expected phase that is

accurate to within one radian from the beginning of the signal to its end. Normally, predictions (templates) are members of families parameterized by quantities such as the masses of the objects, their separations, their spins, and so on. Therefore, detections are made by computer analysis, searching over families of templates for the best match. The sensitivities of detectors can be limited by the available computer power.

- Detectors have very broad quadrupolar antenna patterns. "Pointing" is done by data analysis, by finding the location on the sky that gives the best match to the observed phase evolution.
- Signal-to-noise estimates in this field are usually given in terms of amplitudes: one must square them to compare them with flux-based signal-to-noise figures usually quoted in astronomy (e.g. photons of signal compared with photons of background).

2. The LISA Mission

2.1. *A shared international mission*

LISA has a long history of development, but the present mission was adopted by the European Space Agency (ESA) as a Cornerstone Mission in its Horizon 2000 forward-planning exercise in 1995. In order to share costs, risks, and scientific expertise, ESA and NASA have more recently agreed to share the mission 50-50, and they have established the 20-member LISA International Science Team to guide the first development phase of the mission.

According to the current plan, LISA will be launched in 2011, will arrive at its station in 2012, and will begin returning observations by 2013 for up to 10 years. In 2006 ESA will launch the technology-demonstration satellite SMART-2, carry two LISA-related payloads, one from each agency. The idea of SMART-2 is to test concepts for the reduction of environmental noise and the control of the measurement system, before going into the full mission.

LISA will consist of three spacecrafts arranged in a roughly equilateral triangle. The three sides can be taken in pairs to form two independent interferometers. The spacecraft are separated by 5×10^6 km and communicate by laser beams. In the next section I will describe their working in more detail.

LISA will orbit in the Earth's orbit around the Sun, about 20° behind the Earth. The cluster of three spacecrafts forms a triangle in a plane tilted

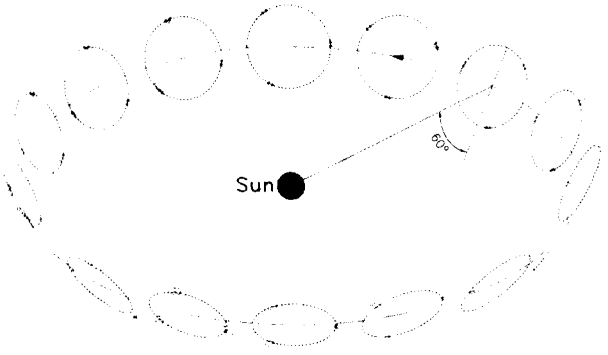

Figure 2. The orbit of LISA shown as 16 snapshots at different times. Notice that the plane of the cluster always faces the Sun and the triangle (only two of whose arms have been emphasized) rotates backwards in this plane.

by 60° to the ecliptic. The unique feature of this arrangement is that, as the spacecrafts follow their independent Newtonian orbits around the Sun, the plane of the triangle remains tilted at 60° to the ecliptic, but the plane rotates so that it always faces the Sun. Moreover, the orientation of the triangle in the plane rotates backwards. This is illustrated in Fig. 2.

2.2. *LISA interferometry*

LISA operates by laser transponding, which means that the laser from one spacecraft is detected by another and sent back in phase and *amplified* rather than just reflected. A reflected beam would be too weak to be seen after traveling 10^7 km, but with well-designed transponders, lasers with a power of only 1 W are sufficient for the interferometry in LISA.

The interferometry in LISA is done by taking so-called "proof masses" at each end of each arm as the reference points for the measurement of distances. The light is reflected from these masses before it is amplified and returned along the arm. Each proof mass must be as undisturbed as possible by external effects, such as the solar wind or solar radiation pressure. The isolation is effected by using the spacecraft themselves as shields, allowing two proof masses to float freely inside each spacecraft. The spacecraft must sense the positions of the proof masses, and when disturbances threaten to make it collide with either of them it fires gentle positioning jets (called FEEPs) to counteract the external forces. This drag-free design is simple and elegant, and very effective. SMART-2 is designed mainly to test the drag-free concept, which cannot be proved on the ground.

Each spacecraft in fact houses four working lasers: one for each remote spacecraft and two to carry signals between the two proof masses in each spacecraft. These comparison signals perform the function that, in a standard Michelson interferometer, would be performed by sending light from the two arms to the output port to form an interference pattern. The three spacecrafts therefore measure signals — variations in phase — from a total of twelve lasers. There is enough redundant information in these signals to control for the effects of laser frequency noise and still leave effectively four signals that contain strain information.

Three of these strain signals correspond to the Michelson interferometer signals from each of the three different pairs of arms. At low frequencies, these are redundant, since any pair of arms could be constructed from the other two. This is not true at frequencies high enough that a reduced gravitational wavelength is shorter than the arm-length; then the time-delay of the gravitational wave as it passes across LISA produces different signals in all three combinations. The fourth strain signal combination is interesting in that, at low frequencies, the gravitational wave signal cancels out completely, so that the fourth signal measures directly the instrumental noise. This will be a valuable consistency check for LISA operations.

3. LISA Science Drivers and Issues

3.1. *LISA sensitivity*

The sensitivity of LISA is summarized in Fig. 3, which gives a more quantitative view than in Fig. 1. The sensitivity curve of LISA is shown for a one-year observation. Some sources, such as the black-hole mergers, last less than a year, so their location is chosen so that they have the right signal-to-noise ratio relative to the sensitivity curve. It is clear that the strongest sources are also the most distant: the mergers of supermassive black holes in galactic centers.

A single point is also shown for a typical capture of a small black hole by a supermassive one. The signal-to-noise ratio is not very large, but the information contained in such a signal is very valuable. Since the inspiralling black hole may execute tens of thousands of orbits before it falls into the supermassive black hole (already taken into account in the computation of

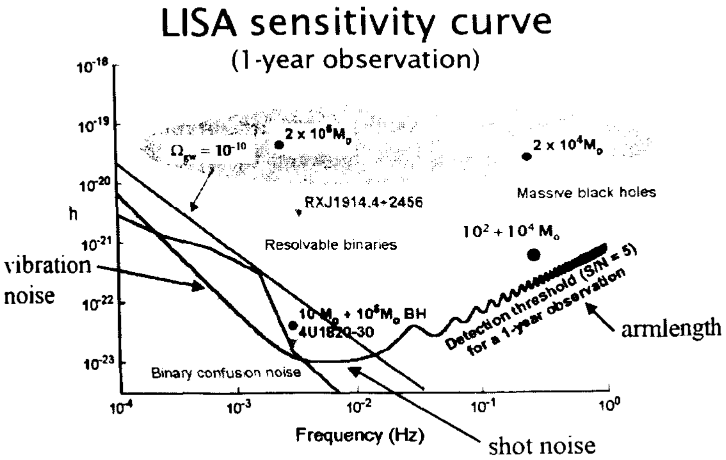

Figure 3. A more accurate indication of the sensitivity of LISA to astronomical sources. The vertical axis is the amplitude of the gravitational wave. The solid curve is the detection limit in a one-year observation with one of the three strain signals discussed above. This limit is set at a signal-to-noise ratio of 5, and it allows for the fact that the sensitivity of LISA to a fixed source on the sky varies during the year of observation because of the rotation of the LISA triangle as it orbits the Sun. Various sources are indicated, as are the limiting noise sources in different frequency ranges.

the signal-to-noise ratio in the diagram), by matching its phase evolution we can make a delicate test of the geometry of the supermassive hole itself, and thereby verify the black-hole uniqueness theorems of general relativity.

The figure shows a shaded region where LISA should resolve (i.e. detect individually) hundreds of white-dwarf binary systems. Contained within this region is a more darkly shaded region where there are too many sources to resolve, and the signals from these form a noise that limits the sensitivity of other observations.

The straight declining diagonal line shows where a cosmological background of gravitational waves would appear as a noise in the observations, if the background radiation field has an energy density of 10^{-10} of the closure density and a scale-free spectrum. Because LISA has the strain signal that does not respond to a gravitational wave, it can distinguish such a noise from instrumental noise. And because the cosmological signal should be independent of direction as LISA rotates, it should be able to distinguish it from the binary confusion noise.

The figure also shows the cause of the limiting noise at each frequency band. The left-hand rising noise limit is due to external vibrations, such as solar radiation pressure. The drag-free control system removes much of this noise, so the curve drawn is the current best estimate of what will be left. The flat bottom of the curve at mid-range frequencies is shot noise, limited by the power of the laser and the sizes of the mirrors. The rising noise to the right is also shot noise, but it increases because at these frequencies the reduced gravitational wavelength is smaller than the arm-length. The result is that the effect of the wave cancels out and the stretching of LISA's arms is less. The wiggles in the curve arise from the fact that the effects are more pronounced when there are an integer number of wavelengths along an arm.

3.2. *A list of science issues*

There are many aspects of LISA science and related astrophysics that need clarification, either to finalize aspects of its design or to prepare for the data analysis. There are also open questions that LISA can shed light on if they are not answered beforehand. Here is a very condensed summary.

- *Merging supermassive black holes in galactic centers.* We would like to know more about the formation and growth of SMBHs and the relation of their mergers to galaxy mergers. We would like to know if there are indicators of mergers from other observations. If galaxy hosts for distant mergers can be identified and their redshifts measured, then LISA may be able to trace the acceleration history of the universe with high accuracy[4,5]. A number of groups today are simulating mergers on supercomputers[6,7], with the aim of making accurate predictions of waveforms. These will be crucial to measuring the masses and spins of the holes accurately and removing their large signals from the data stream without contaminating it and obscuring weaker signals.
- *Signals from the gravitational capture of small black holes by SMBHs.* As mentioned above, these signals contain a great deal of information. To extract it requires a good waveform prediction, and this is a task for theoretical general relativity: we do not yet have an adequate solution of the "restricted two-body problem", allowing us to calculate radiation reaction on small bodies orbiting Kerr black holes[8]. Even if we have waveforms, we are not yet sure how to do the optimal data analysis over huge parameter spaces of waveforms when several strong signals are arriving at once from

different directions, and hundreds of weaker signals are merging into a confusion background. Finally, we would also like better estimates of the capture rate, which requires a deeper understanding of the evolution of star clusters near SMBHs.

- *Survey of all galactic binaries with sufficiently short periods.* LISA can return key information about the population statistics of these elusive binaries, especially since a gravitational-wave polarization measurement determines the inclination angle of the binary and resolves the ambiguities of optical observations. Besides measuring the statistics of white-dwarf binaries, LISA will detect all the short-period neutron-star binaries in the Galaxy and may even see one or two black-hole binaries. The neutron-star observations can be followed up by radio investigations to help determine pulsar beaming fractions and lifetimes. Of course, a key challenge will be to dig as deeply into the confusion limit as possible.
- *Gravitational wave backgrounds.* LISA will detect or limit astrophysically generated backgrounds (from capture events and/or compact binaries) and from the Big Bang. More study is needed of how to determine whether the background is local (i.e. anisotropic) or cosmological and of how accurately LISA can measure its spectrum. If LISA can shed light on the physics of the very early universe, it will constrain fundamental physics theories, such as those that postulate branes or strings.
- *Bursts, unexpected sources.* LISA may well detect radiation from bursts as black holes of intermediate to large mass form in the early universe. There may be more exotic sources, such as cosmic string kinks and cusps[9]. A serious issue, shared with ground-based searches, is to recognize unexpected but real signals.

4. Gravitational Wave Astronomy at High Senstivity

LISAs studies of SMBHs can achieve amplitude signal-to-noise ratios of several thousand, the equivalent of having 10^7 signal photons in an observation for every one of the background. This is far more sensitivity than, say, NGST will have on sources at similar distances. So forget the impression you may have gained from what you have heard about ground-based detectors, that gravitational-wave observations will be marginal detections: LISA will be one of the most powerful astronomical observatories ever constructed.

LISA will study the dark side of the Universe, all sufficiently relativistic and sufficiently clumpy matter regardless of whether it shines or not. Some of this will be associated with things we already know about and can expect, like SMBHs. But some may be invisible to us today. Is the dark matter smooth, or does it have a self-interacting component that has invisible structure of its own? Only gravitational wave observations will be able to answer that question. If LISA follows the examples of pioneering satellites in other observing windows, like X-ray or gamma-ray missions, then we should expect the unexpected!

References

1. L.S. Finn, ed., *Proceedings of the Fourth LISA Symposium* (AIP Conference Proceedings, to be published).
2. K. S. Thorne, et al, "The Scientific Case for Advanced LIGO Interferometers", `http://elmer.tapir.caltech.edu/ph237/Kip-SciCaseAdvLIGO.pdf`.
3. B.F. Schutz, *Class. Quantum Grav.* **16** A131-A156 (1999). Electronic version: gr-qc/9911034.
4. B.F. Schutz, in *Lighthouses of the Universe*, ed. Gilfanov, M., Sunyaev, R., and Churazov (Springer, 2002). Electronic version: gr-qc/0111095.
5. S. Hughes, *Mon. Not. Roy. Astron. Soc.* **331** 805 (2002).
6. J. Baker, M. Campanelli, C. Lousto, *Phys. Rev.* **D65** 044001 (2002).
7. M. Alcubierre, B. Brgmann, D. Pollney, E. Seidel, and R. Takahashi, *Phys. Rev.* **D 64**, 061501 (2001).
8. L. Barack and A. Ori, *Phys. Rev. Lett.* **90**, 111101 (2003).
9. T. Damour and A. Vilenkin, *Phys. Rev. Lett.* **85**, 3761 (2000).