

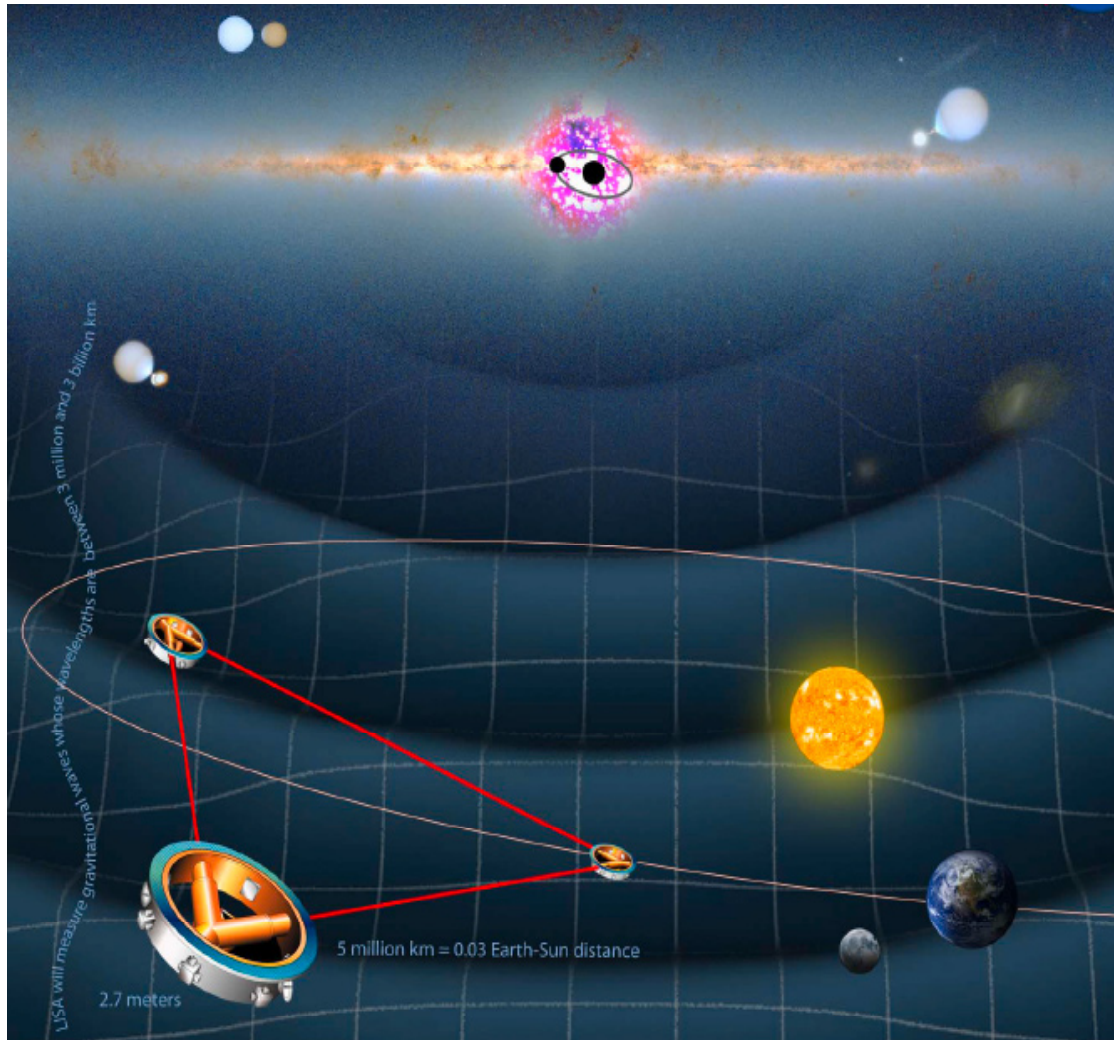
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the LISA newsletter

# Dear Readers!

Welcome to the second issue of the LISA Newsletter. As the ESA and NASA LISA Mission Scientists, we welcome this chance to share with you some of the key science questions LISA will address, challenges we are facing, and progress to date.

LISA is a unique, first-of-its-kind facility for astronomy and physics that will open a huge discovery space unreachable from ground and untapped by any other space mission. LISA offers us the opportunity to study powerful sources that have been predicted and described in great detail by theory but have never been observed because they are “dark” electromagnetically. These include merging massive black holes and non-interacting ultra-compact binary systems, as well as compact objects spiraling into the massive black holes that are believed to exist in the central regions of most normal galaxies. LISA will provide precise measurements of the key properties of massive black holes – masses, spins, and distances, in many cases better than one percent. The ability to provide precise distance information to its sources makes LISA an especially valuable type of astronomical observatory. But that’s not all: LISA science is *new* science, so in addition to guaranteed and predicted sources, we also “expect the unexpected” from this uncharted territory.

LISA’s science can be divided into five general categories. One of them is the astrophysics of black holes. An article by Marta Volonteri in this issue will introduce you to how LISA will be used to study massive BHs in the young and old Universe. In this area, LISA will address such questions as: How and when did the massive BHs in galactic nuclei form? Did they grow mostly by disk gas accretion, or by frequent mergers of smaller BHs in the young galaxies of the high-redshift Universe? Are the BHs in galactic nuclei spinning, and if so, what determines their spin and how did they evolve? If most are found to be highly spinning (say  $a/M \sim 0.8-1$ ), does this imply that the massive BHs form primarily by accreting gas, rather than by mergers of smaller black holes? What are the constituents of the dense stellar cusps in galactic nuclei, and how do they interact with each other?

A second science area will address the question of whether Einstein’s theory of general relativity (GR) remains valid in the “strong-field” regime of gravitation. This will involve studying waves from the mergers of massive black holes and from the inspirals of smaller compact objects into black holes—the so-called Extreme-Mass-Ratio Inspirals (EMRIs), which you may have read about in the first LISA Newsletter. Recall that EMRIs are compact stellar-mass objects (white dwarfs, neutron stars, or black holes) spiraling into massive BHs. At any moment, the trajectory of the compact object is nearly a geodesic of the massive BH spacetime, but gravitational-wave emission causes it to lose energy and angular momentum, and so to spiral in. As we trace its inspiral, we get a map of the spacetime around the massive BH. The elaborate, years-long waveforms generated by EMRIs will give us our most precise measurements of the spacetime structure of black holes.

A third science area is the astrophysics of ultra-compact binary systems involving compact objects such as white dwarfs and neutron stars, orbiting each other with periods from a few seconds to a few hours. LISA is expected to see thousands of individual sources of this type, enough to inform us about the demographics of these objects in our Galaxy, including overall numbers and types (*e.g.*, proportions of neutron-star to BH binaries) and properties such as their angular momentum, chirp-mass distribution, and the scale height of the population of unresolved Galactic white-dwarf binaries. LISA will help answer such questions as: How does the tidal interaction in close white-dwarf binaries work, and how does it influence the evolution and stability of mass transfer? What is the outcome of a common-envelope phase, and what are the ramifica-

tions for our current theories of the formation of compact binaries and of related high-energy phenomena such as gamma-ray bursts, supernovae, binary pulsars, and micro-quasars? How does mass transfer affect the binary dynamics, especially the inspiral–outspiral rates?

A fourth exciting area of LISA science is the precise absolute measurement of distances on cosmological scales. This is an area in which LISA’s complementary information to electromagnetic observations provides a fantastic key to greater understanding. LISA will determine the distance to black-hole binaries very precisely from their observed waveforms (hence their nickname “standard sirens” by analogy with astronomy’s “standard candles”). LISA can only locate them in the sky to about one degree—a field containing  $\sim 100,000$  galaxies; but astronomers may be able to identify the galaxy producing the LISA signal and measure its redshift. The combined information would provide an unprecedented way to measure the scale of the universe. With multiple sources, we would be able to calibrate the Hubble diagram over a wide range of redshifts ( $z \approx 1$  to 15), constrain additional cosmological parameters such as the curvature of the Universe, and obtain precise information about the properties of “dark energy”.

Finally, by observing gravitational waves emitted at the earliest moments in the life of our Universe, LISA may be able to address a host of questions posed by the most modern of physics—“terascale physics” and “string physics”. Is the world really made of “strings” rather than particles? Did the early universe produce relics such as cosmic superstrings that decay predominantly into gravitational waves? What is the nature of the electroweak phase transition? Did the universe release substantial free energy at TeV scales in the form of macroscopic motions—*e.g.*, as a result of an electroweak phase transition, a late end to cosmic inflation, or stabilization of extra dimensions? What is the nature of spacetime—how many dimensions are there? Are the observational predictions of theories of braneworlds and fundamental strings realized? An article by Craig Hogan in this issue describes how LISA’s data can address these and many other questions about the nature of spacetime, the invisible early universe and inflation, “dark energy”, *etc.*

To help us get ready to analyze the LISA science data and answer these questions, specialized data analysis methods are being developed and verified by several research groups in the LISA scientific community *via* “mock LISA data challenges”. In this issue of the Newsletter, you’ll read about these team efforts and how they are designed to examine the crucial aspects of LISA data collection and analysis. We’re also using this issue of the Newsletter to launch a survey, asking our readers to help us with the serious issue of assessing the relative importance of the different types of observational data that LISA will provide to you, as members of the general LISA science community. Your inputs will help guide the LISA Project in choosing the final mission design, so please answer this survey thoughtfully and give your opinions online at the website for the LISA International Science Community, [www.lisa-science.org](http://www.lisa-science.org). Stay tuned for results of the survey and more exciting LISA science in the next issue of the LISA Newsletter.

Sincerely,

*Thomas A. Prince*  
NASA LISA Mission Scientist

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# LISA: Observing massive black holes in the young and old Universe

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Gravitational radiation from black holes is sometimes described as a “laboratory” for fundamental physics, since the physical properties of black holes tell us much about general relativity in its “strong-field” regime. But for astrophysicists, LISA is more than such a laboratory. It is an “observatory” that will give us new clues about the formation and evolution of black holes. Our present knowledge is still limited.

We know that stellar-mass black holes exist, and we have evidence to conclude that they form as endpoints of the evolution of massive stars. We also have found evidence of another, more exotic class of black holes: dark objects whose masses exceed millions, perhaps even billions, of solar masses. These intriguing systems have been nicknamed “supermassive black holes”, or SMBHs.

SMBHs might be black, but they are far from invisible. The first clue for their existence dates back to the sixties, and it was indirect evidence, through identification of quasars and active galactic nuclei, both in local and in high-redshift galaxies (*i.e.*, when the Universe was very young). The huge power outputs from these tiny sources can be explained only as energy radiated away by matter falling into the deep gravitational potential of a SMBH.

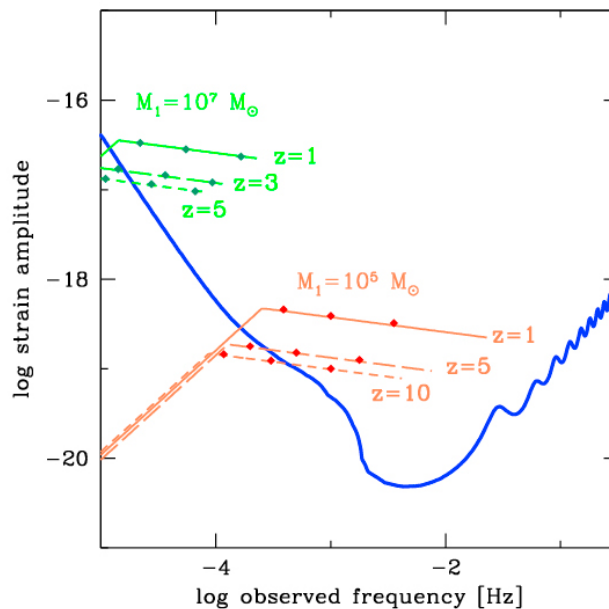
In the last fifteen years, evidence of SMBHs has been found in nearby galaxies, even where there are no signs of powerful activity [Richstone 1998]. Their existence has been inferred from dynamics of the orbits of stars and gas in the innermost regions, dynamics which can be explained only by the influence of the deep gravitational field of a SMBH. The stars are seen to be moving too fast to be a result of the potential generated by the luminous matter alone: a massive object must be lurking in the depths, directing the movements of these puppet-stars.

Although we can infer the existence of SMBHs in galaxies nearby and far away, their formation route remains a mystery. A black hole weighing a billion solar masses cannot be formed simply as the endpoint of a star as massive as a few billion suns, since the gas that would form such a star would fragment into smaller stars before it could become a single proto-star. Smaller black holes, as massive as hundreds, thousands, or even millions of solar masses, could have formed along several possible evolutionary paths in the centers of very distant galaxies, galaxies that existed when the Universe was

very young. It is possible that such “seed” black holes have evolved through time to become the SMBHs that we see now. A famous diagram created in 1978 by Martin Rees [Rees 1978] shows several possible formation scenarios for SMBHs. They divide naturally into two broad groups: one might call them “plus-size” and “petite”. The “plus-size” scenarios predict that black holes begin their lives already quite large—a few tens of thousands of solar masses up to a few million solar masses, formed from the direct monolithic collapse of gas in galactic centers. The “petite” scenarios predict that black holes begin small—perhaps only hundreds of solar masses, formed as endpoints in the evolution of the Universe’s first generation of stars. These first stars are thought to have been much more massive than the current generation, and their remnants could well have been the seeds of today’s SMBHs.

However large or small their initial seeds, once black holes formed, somehow they

evolved to become the SMBHs we see today. The seeds start growing in mass as they accrete the in-falling surrounding matter, and while this is happening, we could expect to be able to observe them as quasars at very high redshift. In fact, we do observe the strongest of such quasars, at distances corresponding to a time when the Universe was only one-tenth of its current age, and we infer that they are powered by billion-solar-mass black holes. No doubt there are “mini-quasars” powered by smaller black holes (with masses of a few thousand solar masses, say), which formed at even earlier times; unfortunately, we do not have observational technology sophisticated enough to detect them. Future planned X-ray missions such as *XEUS* and *Constellation-X*, or near-infrared facilities such as *JWST*, will be able to detect accreting black holes as small as about a few million solar masses in the very early Universe [Salvaterra 2006]. Observation of the putative seed black holes themselves, whose masses range from between a hundred and a million solar masses,



Characteristic strain amplitude for representative SMBH binaries expected to coalesce within the LISA measurement band. The green and red curves correspond to primary masses of  $10^7$  and  $10^6$  solar masses, respectively, with companions of mass  $0.1 M_1$  and redshifts as labeled. The thick blue curve is the limiting strain sensitivity set by LISA’s estimated measurement noise. LISA will observe the inspirals, where strain amplitudes decrease slowly as  $f^{-1/6}$ . Below the “knees” one can see the accumulating signal while the observing intervals are shorter than the time spent by the binaries at a given frequency. The matched-filter signal-to-noise ratio is roughly five times the ratio of the characteristic source strain amplitude to the noise strain amplitude, at the point where this ratio is maximum; *e.g.*,  $\sim 200$  for the red curve at  $z = 1$ . SMBH binaries will be visible to LISA up to high redshift.

## LISA: Observing massive black holes in the young and old Universe (continued)

is nevertheless beyond the capabilities of any planned X-ray and near-infrared missions.

The ability to observe gravitational waves has astrophysical implications beyond understanding the birth and evolution of single massive black holes. The *mergers* of black holes that exist in binary systems will be visible to LISA even for black holes as small as just a thousand solar masses, almost independent of their redshift. The mergers of mature supermassive black holes should represent the brightest and loudest sources for LISA. The signal-to-noise ratio is more than a thousand for binaries with masses of  $10^6$ – $10^7$  solar masses up to redshift  $z = 1$ , corresponding to a few Gpc. The signal-to-noise ratio remains around a few hundred for black holes with masses of  $10^5$ – $10^7$  solar masses up to redshift  $z = 5$ , corresponding to a few tens of Gpc. This is an interesting redshift and mass range, as it includes a large fraction of the active galactic nuclei observed. The black hole at the center of the Milky Way itself, which weighs an estimated four million solar masses, falls into the sweet spot as well.

The questions asked by astrophysicists studying supermassive black-hole mergers deal both with the *number* of SMBHs in the Universe, and the *dynamics* and *efficiency* of the merger process. How often a galaxy hosts a black hole influences the number of binaries that can form. The dynamics and efficiency of black-hole mergers in galactic centers determine how many of the binaries can actually get into the interesting regime for gravitational-wave detection. When two galaxies both hosting central black holes merge, simple physical arguments suggest that the black holes can indeed sink (by dynamical friction) to the center of the merged galaxy, and form a binary system with separation of around a parsec. Emission of gravitational radiation, however, could bring the binary to coalescence in less than a Hubble time only if the separation is about two orders of magnitude smaller. How to bridge the gap (“the final parsec problem”) is still a matter of discussion [Merritt 2005]. Among the proposed mechanisms to shrink a binary include scattering with stars (which is much more efficient in triaxial galaxies or galaxies with rotation), or the interaction of the binary with gas, possibly in the form of an accretion disc.

Different theoretical models for the formation of SMBH seeds and for the dynamical evolution of black hole binaries predict different event rates for black-hole merger events [Berti 2006; Volonteri 2006]. Earlier

estimates, based only on observed quasars, and not accounting for small ( $< \text{few million solar masses}$ ) or high-redshift ( $z > 3$ – $4$ ) black holes, gave pessimistic rates, lower than a few mergers per year. Most other estimates are much more optimistic. Conventional scenarios, based on standard cold dark matter cosmology, predict that black holes experience a hierarchical assembly jointly with their host galaxies, resulting in rate estimates of several tens of black hole mergers per year in the range accessible to LISA. All of these models are compatible with present-day observational constraints, in particular the ubiquity of SMBHs in nearby galaxies. LISA’s detections will eventually settle enduring debates among astrophysicists on the number of massive black holes, the dynamics of black hole binaries, and the efficiency of mergers.

The number and masses of black holes are not the only features of the black-hole population that LISA can help measure. Astrophysical black holes are characterized by two parameters: mass and spin. Theory predicts that a large fraction of SMBHs should be spinning rapidly, due to interaction between the black hole spins and the angular momentum of the accretion disc. This prediction is still to be proved. Measuring SMBH spins is an arduous task, and all current evidence is indirect. One technique is based on the shape of the X-ray iron line from the inner disk of accreting SMBHs, which has been observed in several local Seyfert galaxies, including MCG-6-30-15 [Miniutti 2004]. Detection and unambiguous interpretation of the iron line, however, is problematic for most sources. In contrast, the detection of gravitational waves from merging binaries will provide a unique tool to measure SMBH spins. LISA should be able to measure masses and spins to a percent for weak sources, and 0.01 percent for strong ones.

Astronomers know that multi-wavelength observations are the best way to understand the physics behind a source. LISA, as a gravitational-wave observatory, can be viewed as another instrument working at a somewhat *special and unique wavelength*, part of a larger network of observatories, others of which operate in the electromagnetic bands. Electromagnetic observations of a merger precursor, during the last few years of inspiral, or of an afterglow within a few years after coalescence, may highlight sky positions of galaxies hosting gravitational-wave sources observed or observable by LISA. The identification of electromagnetic counterparts would help us understand the nature of host galaxies, and

to grasp the dynamics of black holes merging in galaxy centers [Dotti 2006]. Electromagnetic precursors are expected to accompany binaries with components more massive than about 10 million solar masses (unlikely to be detected by LISA). They would manifest as transient, highly-variable X-ray sources, which would turn off at black-hole coalescence. Afterglows, on the other hand, are most interesting for smaller black holes. For binaries with components less massive than a million solar masses, gas would refill the accretion disc within a few years after coalescence [Milosavljevic 2005]. The afterglow would manifest itself as a bright, steady X-ray source. A newly-born active galactic nucleus (AGN) in the LISA error cube ( $0.1$ – $1$  square degrees in the sky with a depth of  $\sim 0.01$ – $0.1$  in redshift [Lang 2006] would be a clear signature of recent merging, and would allow identification of the host galaxy, enabling a new era of precision cosmology and dark energy measurement [Dalal 2006].

### References

- Berti E, *et al.* 2006 “LISA observations of massive black hole mergers: event rates and issues in waveform modeling” in *Proceedings of 10th Annual Gravitational-Wave Data Analysis Workshop*, *Class Quantum Grav* **23**, S785–S798
- Dalal N *et al.* 2006 “Short GRB and binary black hole standard sirens as a probe of dark energy” *Phys Rev D* **74**, 063006
- Dotti M *et al.* 2006 “On the search of electromagnetic cosmological counterparts to coalescences of massive black hole binaries” *MNRAS* **372**, 869–875
- Lang R, Hughes S 2006 “Title: Measuring coalescing massive binary black holes with gravitational waves: The impact of spin-induced precession” gr-qc/0608062
- Merritt D, Milosavljevic M 2005 “Massive black hole binary evolution” *Living Reviews in Relativity* **8**, 8 <http://www.livingreviews.org/lrr-2005-8>
- Milosavljevic M, Phinney E 2005 “The afterglow of massive black hole coalescence” *ApJ* **622**, L93–L96
- Miniutti G, Fabian A, Miller J 2004 “The relativistic Fe emission line in XTE J1650-500 with BeppoSAX: evidence for black hole spin and light-bending effects?” *MNRAS* **351**, 466–472
- Rees M 1978 “Emission from the nuclei of nearby galaxies – Evidence for massive black holes” in *Structure and Properties of Nearby Galaxies: Proceedings of the Symposium*, D. Reidel Publishing Co. 237–242
- Richstone D *et al.* 1998 “Supermassive black holes and the evolution of galaxies” *Nature* **395** A14
- Salvaterra R, Haardt F, Volonteri M 2006 “Unresolved X-ray background: clues on galactic nuclear activity at  $z > 6$ ” *MNRAS* (in press) astro-ph/0610329
- Volonteri M 2006 “Supermassive black hole mergers and cosmological structure formation” in *Proceedings of the Sixth LISA Symposium*, AIP Conf Series, astro-ph/0609741

# LISA and new physics: Gravitational waves in the stringy Universe

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## What is the world made of?

In the ancient world, thinkers such as Leucippus, Democritus, Lucretius and others argued persuasively that the world must be made of very small pieces called atoms. More than two thousand years elapsed before quantitative experimental evidence showed that matter really is composed of atoms. Only after the discovery of radioactivity by Becquerel in 1896 (triggered by his accidental discovery of fogged film during a pause in an investigation of solar radiation) were physicists able to measure real properties of elementary particles. Soon after that came modern physics and quantum theory, and the resulting revolution in technology that continues to this day. It is now believed that the world (including atoms) is made up of quantum particles and fields, described by the “Standard Model” with possible extensions, which propagate in a curved, three-plus-one-dimensional classical spacetime (described by Einstein’s theory of General Relativity).

These days, the deep thinkers of science tell us that the world is not made of particles, but of strings. The new ideas provide a self-consistent mathematical framework for the ideas that dominated 20<sup>th</sup>-century physics, and they extend those ideas profoundly.

The world according to “string theory” has many layers, each rich with hidden mathematical structure. Certain constituents of the world, such as matter particles and gravitational waves, are explained as possible characteristics, or properties, of quantized one-dimensional (“1D”) string-like objects, which propagate in ten dimensions of space, seven of which are so small as to have hitherto been invisible to us. One hypothesis is that the particles and fields we know are 1D strings whose ends move on microscopically-thin quasi-classical surfaces called “3-branes”, which fill the three large, familiar dimensions of space and are embedded in a 10-dimensional space. Seven of the dimensions are much smaller but may still be relatively large by microscopic standards since they are visible only to gravitation and not to other fields. Here “relatively large” means that they could be as large as 0.2 millimeter – the size of a very small bug, say – a limit set by laboratory tests of the inverse-square law of gravitation. Another possibility is that all ten dimensions are actually infinite, but the seven we haven’t detected are highly *curved*, with a curvature scale smaller than 0.2 millimeter.

Gravitational waves penetrate into these extra dimensions, and in some cosmologies, as discussed below, LISA can detect waves associated with the stabilization of this configuration of spacetime and branes in the early universe.

Another intriguing conjecture arising from these new ideas is that the behavior of the 3+1-dimensional world (3 space plus 1 time dimension), with its stringy fields and quantized gravity, is mathematically equivalent to that of a 2+1-dimensional quantum world characterized by “strong interactions” among its constituents. This “holographic” quality could in principle have detectable effects on the behavior of gravitational quanta.

These new ideas are mathematically compelling, and they offer a rich variety of possible new phenomena. This makes it all the more perplexing that we have as yet found no physical evidence for their existence! All experiments to date are fully explained by the Standard Model and its field-theory extensions in 3+1-dimensional spacetime. Even exotic cosmic phenomena such as cosmic dark matter, dark energy, and inflation can be accounted for within the framework of relativistic cosmology with field theory. Although these effects have demanded new physics of one sort or another, they are all describable with straightforward field theories; in other words, we have detected no features about them that are undeniably “stringy”. How then can we ascertain whether the world is indeed made of strings, or has more than three dimensions of space?

## LISA and the Terascale: listening for loud Big Bangs

One possibility for answering these questions in the near future lies in accelerator physics. The Large Hadron Collider will start producing data in the coming years at Terascale (TeV) energies. This scale, which corresponds to temperatures on the order of  $10^{16}$  K and gravitational timescales of  $10^{-12}$  sec, is the scale at which some of the “effective fields” of the Standard Model, such as the Higgs field that produces symmetry breaking, should start to display their underlying structure. There is high hope that evidence might be uncovered of supersymmetry, a symmetry that connects the properties of matter and radiation, and which is a central component of string theory. It is possible that new degrees of freedom in extra dimensions may be observably excited,

or even that the accelerator may produce tiny ephemeral black holes.

As mentioned above, extra dimensions can also be probed in the laboratory. Experiments at the University of Washington, which use the same torsion-balance technology currently being applied to characterize tiny acceleration disturbances to the LISA measurement apparatus (see article in this issue), tell us that the inverse square law of gravity holds down to about 0.2 mm, hence the size or curvature scale of extra dimensions must be smaller than this.

There are also ways to probe the Terascale using cosmology. If we can observe features of the universe as far back as the very beginning of the Big Bang, when temperatures corresponded to about 1 TeV, we would, in effect, be exploring exactly this energy scale. The spacetime curvature radius (roughly the distance light travels in the time it takes the universe to double its size) at that time was less than about a millimeter, so relics of our universe from before this epoch could reveal to us features of gravity, and possibly extra dimensions of space, that now lie beyond our understanding.

Two famous examples of such primordial relics, both of which pre-date the Terascale by what might be a very large factor, are the cosmic excess of matter over antimatter (also expressed as the mean ratio of baryons to primordial photons), and the large-scale structure of the universe itself, including the cosmic expansion and its fluctuations. The first effect probes new particle interactions; the second probes global structure on the very largest scales, millions to billions of light years today, usually explained using inflation theory.

Last but far from least, the emerging science of gravitational waves now opens up a profound and potentially rich means of exploring the cosmological Terascale and beyond. Gravitational waves propagate freely everywhere; hence they reach us from the entire history of the Universe—right back to the start of the Big Bang, whenever that was. That history includes great stretches of hitherto “invisible ages”, about which we as yet have no data concerning either the microscopic composition or global properties of our universe.

As noted above, at a cosmic temperature of about 1 TeV, the size of the classical horizon is about 1 millimeter. A gravitational wave

## LISA and new physics: Gravitational waves in the stringy Universe (continued)

of that wavelength, redshifted to the present day, has a frequency of about 0.1 milliHertz ( $10^{-4}$  Hz)—near the central, most-sensitive part of LISA's measurement band. LISA and other planned gravitational-wave observatories will be exploring classical sources of gravitational waves within the horizon scale at Terascale energies and above. This represents a new unexplored territory that lies, in log space, about halfway between microscopic (Planck) and astronomical (Hubble) scales, and about halfway back to the standard inflationary epoch. LISA will be the most powerful tool for exploring gravitational activity on this “mesoscopic” scale of cosmology, over a range of temperatures from about 0.1 to about 1000 TeV. Because other particle relics are absorbed and thermalized, this period is accessible to direct observation only by gravitational waves.

Mesoscopic gravitational waves might be connected in profound ways to many of the new physics ideas noted above. Some extensions of the Standard Model that will soon be tested at the Large Hadron Collider predict a first-order phase transition near the Terascale, which creates turbulence (like boiling water turning to steam) and produces strong gravitational waves. The creation of baryons is often thought to arise during such a process. The end of inflation, a process of re-heating that converts a highly-ordered inflation field into a thermalized plasma, might have cascaded internal inflation energy through kinetic motions on the mesoscopic scale, and this also might have created a great cacophony of gravitational waves deposited at the Terascale—a “loud Big Bang”. It is even possible that the formation of our 3-brane, or the stabilization of some of the extra spatial dimensions at the sub-millimeter scale, produced copious relic gravitational waves. All of these effects might produce a stochastic background of gravitational waves with intensity sufficient for LISA to detect them easily. Indeed, since LISA is opening a completely new discovery space in cosmology, non-detection will also provide profound constraints on models of matter and energy beyond the Terascale.

### A symphony of strings: backgrounds and bursts from superstring loops

In addition to these primordial relics of the birth of our universe, theorists have imagined an even more exotic source of gravitational waves—inherently stringy objects called “cosmic superstrings”. Although created in the early universe, they may

be present in the universe today. Cosmic superstrings would fill the universe with gravitational radiation. While their other effects may be completely unobservable, they could well dominate the gravitational waves observed by LISA.

Fundamental, microscopic quantum strings in some circumstances condense into quasi-stable, quasi-classical superstrings, which are microscopically thin but astronomically long 1-branes. In the early universe, a dense network of these form after inflation by quenching, a process that resembles the formation of trapped vortex lines seen in sudden cooling of superconductors, superfluids, or liquid crystals. As the universe expands, the superstrings unravel and rush around at almost the speed of light. When they cross they exchange partners, spawning a population of closed loops of superstring. The loops thrash around over and over but stay around for a long time, shrinking only slowly. In fact, the main way the loops lose energy is by emitting gravitational waves! These gravitational waves are the most conspicuous effect of superstrings, since their other interactions are too weak to produce any detectable effects in the universe.

Estimates of the strength of gravitational waves from superstrings imply that they produce a stochastic background easily detectable by LISA, for many scenarios suggested by string-theory inflation. Even more exciting, this background spectrum is distinctive enough to serve as a quantitative diagnostic of string properties.

The most interesting events from these loops happen on rather rare occasions when by chance a loop beams gravitational waves in our direction by a sort of whipping action, described in mathematical formalism as a cusp catastrophe. At one instant the motion of one piece of the string approaches the speed of light, and as this moment approaches, the gravitational waves it emits are beamed into a narrow angle at frequencies far above the fundamental frequency of the string loop, given by its inverse length. Superstring bursts have a universal waveform that corresponds to one type of mathematical catastrophe, which ensures that it has a well-defined predicted signature in both time and frequency. On the other hand they are probably harder to detect with LISA than the confusion background of all the loops put together.

Measurements of a background or of bursts of superstring gravitational radiation would provide insight into physics beyond the Standard Model and classical general relativity, and particularly into the physics underlying cosmic inflation. Real observational data will go a long way toward shaping the rich mathematical insights of string theory into a model of the real world.

It may seem odd that, in order to find evidence of fundamental stringiness, the basic structure of everything surrounding us in our world, we must listen for barely detectable phenomena at the far corners of the universe. But then, who would have guessed that our first clues to the particle nature of all matter would come only from salts of exotic radioactive metals? Or that evidence of elementary particles would come from energetic cosmic rays from outer space? Or that events as powerful as supernova explosions, so bright that they were causes of wonder to ancient astronomers, would be driven by neutrinos, particles so hard to detect that their masses and interactions could not even be measured until the 21<sup>st</sup> century? The universe shown to us by gravitational waves might be rich with signals that reveal facts and aspects of new physics which we have as yet not even guessed.

### References:

Hogan C 2006a “Gravitational waves from light cosmic strings: backgrounds and bursts with large loops” *Phys Rev D* 74, 043526

Hogan C 2006b “Gravitational wave sources from new physics” in *Proceedings of the Sixth International LISA Symposium*, AIP Conference Proceedings, New York: American institute of Physics, astro-ph/0608567

LISA will be the first space-based laser interferometer gravitational-wave detector. There are compelling reasons for moving to the disturbance-free environment of space. The interferometer arms can be made very long, more than a million times longer than the longest ground-based detector. Increasing the length amplifies the effect of gravitational waves and enhances the detector's low frequency sensitivity. One disadvantage of space is that the LISA constellation will be subject to the gravitational whims of the solar system. The orbits of the three LISA spacecraft will be perturbed by the gravitational attraction of the earth. These perturbations pose several challenges for the LISA interferometry.

When using laser interferometry to measure displacement, the wavelength of the laser plays the role of yardstick. A change in the laser wavelength (or equivalently the laser frequency) will be interpreted as a change in measured separation of the proof masses. Consequently, a strain sensitivity of  $10^{-20}$  requires a frequency stability of 1 part in  $10^{20}$ , far beyond the capability of any laser system. If two equal-length arms are measured using the same laser wavelength, then the effect of laser frequency noise is common to both measurements and will cancel when their difference is taken. A Michelson interferometer, a good example of such a difference measurement, forms the basis for ground-based interferometric gravitational-wave detectors. The gravitational-wave strain, however, will affect non-parallel arms differently and so will not cancel.

The cancellation of laser frequency noise is limited by the length matching of the arms. It is hard to match the LISA arm lengths to much better than 1% for extended periods of time. Over a year the LISA spacecraft separation changes by approximately 100,000 km, with up to 15 m/s drifts. Compare this to LIGO interferometry, where the Earth's tide induces a change in proof mass separation of around 100  $\mu\text{m}$  with approximately a 10  $\mu\text{m}/\text{hour}$  drift.

The plan to limit the impact of laser frequency noise starts with the choice of a Nd:YAG non-planar ring oscillator laser system, one of the most inherently stable lasers. The laser will be pre-stabilized to an ultra-stable reference cavity. Under ideal circumstances, the relative length stability of the optical cavity is transferred to the relative frequency stability of the laser. A cavity constructed from ultra-low-expansion glass housed in a micro-Kelvin stability environment has been

shown to yield a laser frequency stability of better than  $10^{-13} / \sqrt{\text{Hz}}$ .

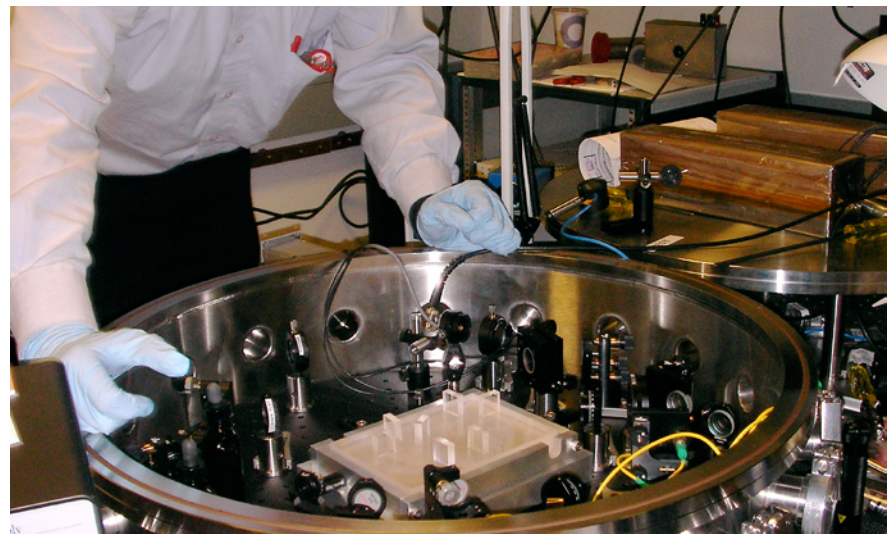
Frequency pre-stabilization is ultimately limited by the length stability of the reference cavity. The most stable length reference over the time scales of interest is a LISA arm. If the arm is stable enough to detect gravitational waves then it is overqualified for use as a length reference. For times longer than the roundtrip travel time, the laser frequency can be locked to the arm length. This technique, known as arm locking, is used in some form in every ground-based detector. The situation is slightly more complicated in LISA due to the need for high-bandwidth feedback in the presence of a long delay. The standard approach to a control system with a delay is to limit the bandwidth, and therefore the gain of the control loop, to ensure stability. In the case of LISA, this would result in no frequency noise suppression above 15 mHz and only modest reduction at 1 mHz. It has been shown however that high bandwidth feedback is possible with LISA [Sheard 2006]. The interferometric beat-note phase is determined by the phase difference between the local laser and the light returning from the distant spacecraft. The presence of the local laser provides the necessary information to build a high-gain frequency stabilization system. The stability and noise suppression of a high-gain arm-locking style control system has been demonstrated at a number of institutions around the world [Marin 2005; Sheard 2005; Thorpe 2005]. More recently, multi-arm extensions to the basic arm-locking scheme have been proposed that promise significantly better performance [Herz 2006]. In fact, arm-locking implementa-

tions have improved to the point where it may be possible to achieve the required frequency noise suppression with little or no frequency pre-stabilization.

After pre-stabilization and arm-locking the laser frequency noise will still appear several orders of magnitude higher than the target instrument noise floor. This remaining noise will be removed by a technique known as Time Delay Interferometry (TDI). TDI, pioneered by Tinto, Armstrong and Estabrook almost a decade ago, forms linear combinations of the raw phase measurements with very particular delays. TDI exploits the correlations in the frequency noise of the interferometer arms. The gravitational-wave signal is not removed by TDI, as it induces almost opposite phase correlations due to the nature of the differential strain. More recently it has been noted that the TDI combinations correspond to interferometer configurations that have equal length arms. TDI can thus be considered as a method of synthesizing an equal-arm interferometer (see insert).

The main technical challenge with forming the TDI combinations is ensuring that measurements are made at the correct times around the constellation. Precise timing requires precise knowledge of the arm lengths as well as tight synchronization of data streams recorded on the different spacecraft.

Since TDI forms linear combinations of time-delayed phase measurements, it is not surprising that noise suppression is degraded by errors in the delay times used. The needed delay is determined by the travel



LISA interferometry testbed "optical bench" at JPL.

time for light between spacecraft (arm-length/ $c$ ) and, in some cases, by the error in clock synchronicity between spacecraft. The correct delays will be determined by dedicated ranging and clock-synchronization measurements.

In recent years the implementation of TDI has been simplified significantly. Responsibility for sampling the measurements at the correct times has shifted from the flight system to post-processing. Rather than attempt to trigger the phasemeters to sample at the correct times onboard, the data streams will be re-sampled after the measurements by using high-performance interpolation algorithms [Shaddock 2004]. The quality of the interpolation is determined by several factors, most notably the length of continuous data available; more accurate interpolation requires longer stretches of data around the region of interest. With a laser frequency stability of  $10^{-13}$  /Hz, interpolation errors can be kept negligibly low with around 30 seconds of continuous data. Since each TDI combination requires a unique set of delays, an advantage of implementing the time-delays on Earth is that the data streams can be re-sampled as needed to form any TDI observable.

The noise suppression afforded by TDI is also limited by the quality of the raw phase measurements. High-fidelity phase measurements of the laser interference are needed. This is the job of the phasemeter, one of NASA's key deliverables for LISA interferometry. If the proof mass is the heart of LISA then the phasemeter is LISA's brain. The phasemeter accepts information from multiple photoreceivers and extracts phase information, which is transmitted to ground for science processing.

As far as the phasemeter is concerned, the dominant "signal" in a photoreceiver output is laser frequency noise, which is several orders of magnitude larger than the target instrument noise level. Thousands of cycles of frequency noise must be measured with an accuracy of a few microcycles. Achieving this requires exceptional linearity over a high dynamic range. The phasemeter is based on a digital phase-locked loop, a standard building block of many GPS and digital receivers. Sophisticated digital filtering is used to prevent high frequency noise from aliasing into the LISA signal band.

Phasemeter development at JPL has exceeded our most optimistic expectations. After focusing on architecture selection, model-

ing, and simulation in 2004, we began development of a breadboard phasemeter at the beginning of 2005. By mid-2005 the phasemeter had replaced commercial and other custom-made phasemeters in all experiments in our laboratory. Since April 2006 the LISA phasemeter has also been used by Ball Aerospace, Colorado for testing interferometry for the GRACE follow-on mission. The phasemeter has also been selected as the basis for inter-spacecraft ranging for formation flying missions (IN-FOCES) development effort.

An end-to-end simulation of the laser frequency cancellation chain is in its final stages. This simulation, part of collaborative efforts between EADS Astrium of Germany and JPL, encompasses laser frequency stabilization, arm-locking, phasemeter operation, interpolation, and culminates in the formation of the TDI combinations. The goal of the simulation is to characterize the phasemeter performance with realistic signals with the hope of identifying any errors limiting the cancellation of laser frequency noise. The simulation will also help to optimize and balance the noise suppression requirements across pre-stabilization, arm-locking and TDI.

The simulation uses the breadboard phasemeter to perform the phase measurement. This hardware-in-loop approach is not only an accurate simulation of the LISA phasemeter processing, but allows simulation to be performed in real-time compared to about 1% of real-time operation when the phasemeter processing is emulated by desktop computers. So far, the simulation has found no errors with the phasemeter processing for noise cancellation factors up to  $10^9$ . Future plans for extending the simulation include comparing different arm-locking topologies, verifying the effects of clock synchronization and clock noise, and testing of data compression needed for transmission to ground.

Future phasemeter development work will focus on adding functionality needed to support the LISA measurement. For example, the phasemeter also provides information used to control spacecraft attitude, proof-mass orientation and laser frequency control systems. The phasemeter also extracts inter-spacecraft telemetry, and processes clock synchronization and absolute range measurements.

For the phasemeter and TDI to achieve a higher formal rating for its NASA-man-

dated "technology readiness level", performance must be demonstrated in a realistic system environment. NASA's efforts toward this are focused around an interferometry development testbed. Specifically, this testbed addresses "Interferometry Gate 1" in NASA's official LISA Technology Development Plan. To pass this development gate, we must demonstrate that heterodyne phase measurements referenced to independent clocks, formed using multiple laser beams exchanged between multiple end-stations, can be combined in post-processing to suppress the contributions from laser frequency fluctuations.

The testbed is based on the Sagnac TDI combination, commonly denoted as  $\alpha$ . This combination has the same sensitivity to errors in delay (and therefore the same interpolation requirements) as the Michelson-type combinations. The phasemeter requirements are driven by the laser frequency noise and are also independent of which TDI combination is used in post-processing. One advantage of  $\alpha$  is that it allows transparent characterization of measurement errors. Unlike other TDI combinations, each phasemeter output enters the  $\alpha$  combination only once, ensuring that errors in each measurement appear directly in the output, independent of arm-length. This is in contrast to the Michelson-type TDI combinations where the transfer function of the noise is strongly dependent on arm-length. As with all other TDI combinations, the accuracy of the delay is critical to the performance. However, with  $\alpha$  the size of the delay is not important and representative testing of TDI with laboratory-scale arm lengths is possible.

The first stage of the testbed, which is almost complete, consists of a single LISA spacecraft with two dummy mirrors replacing the distant spacecraft. This testbed met its performance requirements for the first time in June 2006. The second stage involves replacing one of the dummy Sagnac mirrors with a second LISA spacecraft. This will allow a second set of lasers with different heterodyne frequencies to be included, exposing the phasemeter to a new class of non-linear noise mixing. It is hoped and expected that the phasemeter will also pass this test. With a demonstrated noise suppression of ten million during stage one of the testbed, together with the recent positive simulation results, we are confident that the phasemeter, interpolation algorithms and TDI combinations will provide the frequency noise suppression LISA requires.

## Time Delay Interferometry

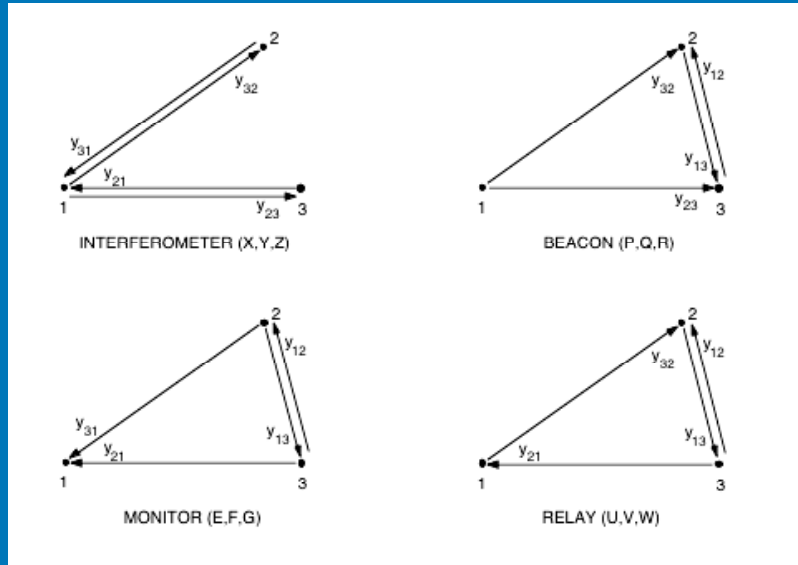
LISA's design sensitivity is set by two things: the gravitational wave (GW) response of the 5-million-km arms and LISA's very low level of optical path and proof-mass acceleration noises. To achieve a noise level set only by optical path and acceleration noises, LISA must first suppress the otherwise overwhelming (by more than six orders of magnitude) contribution from laser phase noise. This will be accomplished with a technique called Time Delay Interferometry (TDI). A thorough tutorial of TDI can be found in [Tinto 2005] and references therein.

Laser phase noise is inconsequential for an ideal equal-arm Michelson GW interferometer, because it is common to both arms and therefore disappears in the differenced phase measurement when the two beams are recombined. Unfortunately, celestial mechanics guarantees that LISA's armlengths will be both unequal and time-variable. LISA's armlengths  $L_1$  and  $L_2$  differ at any moment by up to 1 or 2 percent. In a Michelson arrangement with a common laser having phase noise  $P(t)$ , standard real-time phase-differencing would result in unsuppressed laser phase noise contributing an amount  $P(t - 2L_1/c) - P(t - 2L_2/c) \approx 2(L_1 - L_2) [dP(t - 2L_1)/dt] / c$ . For typical LISA parameters (geometry, laser phase noise spectrum), this suppresses laser noise by 3-4 orders of magnitude at midband. That suppression is not enough; a different approach is needed.

TDI is a signal-preserving way to cancel all laser phase noises in an unequal arm GW detector. TDI had its genesis in milliHertz-band GW searches using Doppler tracking of planetary spacecraft in the 1970s. In TDI's simplest formulation, the "one-way" Doppler shifts on links connecting spacecraft pairs are independently recorded. Those six Doppler time series (" $y$ 's"), along with intra-spacecraft metrology (" $z$ 's"), contain information on all laser noise processes, some with time offsets set by inter-

spacecraft propagation times. TDI treats the LISA system symmetrically, providing linear combinations of the observations ( $y$ 's and  $z$ 's) that cancel noise from all LISA's lasers, even for arbitrarily different arm lengths. Importantly, there are many laser-noise-canceling combinations, each having different couplings to GW signals and the remaining (optical path, acceleration) noises. Figure 1, for example, shows the possible laser-canceling combinations using only four of the six links. Multiple TDI combinations can be exploited to discriminate signal from noise, estimate as-flown noise spectra, localize source-directions, *etc.*

Important practical problems such as spacecraft relative motion and array "flexing" are treated in "second-generation" TDI—the combinations are more complicated, but LISA's laser noises are cancelled to well below the levels of contribution from optical-path and proof-mass perturbations. To implement TDI, armlengths must be known, but only with modest accuracy. Since TDI cancels arbitrary laser phase noises, it works whether or not some of the lasers have been phase locked for other technical reasons (either arm-locking or intra-spacecraft locking between optical benches).



Schematic diagrams of laser-canceling 'first-generation' TDI combinations using only 4 of the 6 possible inter-spacecraft links [1]. The  $y_{ij}$ 's are fractional Doppler frequencies of one-way links connecting spacecraft pairs. The 3 unequal-arm Michelson combinations ("X, Y, Z", the distinction being which of the three spacecraft is the 'central mass'), there are more novel noise-canceling combinations. As with X, Y, Z, permutation of spacecraft numbers 1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  1 gives 3 each of the 'relay', 'beacon', and 'monitor' combinations. (Not shown: the 6-link Sagnac combinations  $\alpha$ ,  $\beta$ ,  $\gamma$  and the fully symmetric combination  $\zeta$ ). GW sensitivities of all combinations are in [1] and references therein.

Tinto M, Dhurandhar S 2005 "Time delay interferometry" *Living Reviews in Relativity* 8, 4 <http://www.livingreviews.org/lrr-2005-4>

### References:

Herz M 2005 "Active laser frequency stabilization and resolution enhancement of interferometers for the measurement of gravitational waves in space" *Opt Eng* 44, 090505

Marin A, *et al.* 2005 "Phase locking to a LISA arm: first results on a hardware model" *Class Quantum Grav* 22, S235–S242

Shaddock D, *et al.* 2004 "Post-processed time-delay interferometry for LISA" *Phys Rev D* 70, 081101–081106

Sheard B, *et al.* 2003, "Laser frequency stabilization by locking to a LISA arm" *Phys. Lett. A* 320, 9–21

Sheard B 2005 "Laser frequency noise suppression by arm-locking in LISA: progress

toward a bench-top demonstration" *Class Quantum Grav* 22, S221–S226

Thorpe J, Mueller G 2005 "Experimental verification of arm-locking for LISA using electronic phase delay" *Phys. Lett. A* 342, 199–220

# Ground tests of the LISA Gravitational Reference Sensor

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When the LISA constellation is in place, some 50 million km from Earth, the only surprises in the data must be signals from unpredicted gravitational-wave (GW) sources and not some instrumental artifact or uncertainty. To assure the purity of the science signals, all conceivable, and perhaps even inconceivable, effects that could mimic or disturb the tiny GW-induced displacements must be discovered, understood, and accounted for.

Among the most crucial components of LISA are the end mirrors of the 5-million-km interferometer arms. These mirrors, called “proof masses”, are solid, 2-kg cubes made of a special Au-Pt alloy with very low magnetic susceptibility. Changes in the relative distances among these proof masses over time scales from one to over 10,000 seconds are monitored interferometrically with precision of a few picometers, in order to detect strain disturbances induced by passing gravitational waves.

Amazingly, it is not the distance measurement itself, performed by the interferometer, that contributes most to the uncertainty at low frequencies (*i.e.*, on time scales longer than about 1000 sec). Rather, it is our ability to insulate the proof masses from disturbances not caused by passing gravitational waves—*i.e.*, from forces that move the proof masses in a noisy or uncontrolled fashion.

The proof masses are freely floating within the spacecraft, which protects them from external forces such as the solar wind, solar radiation pressure, micrometeorites, *etc.* The spacecraft is continuously re-positioned so that it follows the proof masses precisely (“drag-free” operation). To accomplish this, each proof mass is surrounded by electrode plates, which are used to sense capacitively its relative position. The electrodes are also used to actuate the proof masses gently to control their orientation and their position in the directions that are not lined up with the interferometer arms. These electrode plates are embedded in the housing surrounding each proof mass. The proof masses, the electrodes, and the housings form the main components of the gravitational reference sensors (GRS). In the current LISA design, the distance between each proof mass and its surrounding electrodes/housing is between 3 and 4 mm.

At the level of disturbance insulation required for LISA, there are numerous sources

of small forces acting between the surfaces of the proof masses and their surrounding housings. These forces may fluctuate at the frequencies at which LISA is searching for gravitational waves. Since these forces are so weak that they are utterly insignificant in most technical applications, only limited quantitative understanding of them is available. Because of the uncertain nature of these effects, and the possible existence of additional disturbances we have not yet accounted for, the modeling and performance predictions for LISA have to be very conservative, leading to excess margin.

The curves in Figure 1 show the ten largest acceleration-noise terms included in the current LISA noise model (Merkowitz 2006) at the very low end of the measurement band, 0.03mHz. (The ten dominant terms at 0.1mHz are slightly different and smaller than these.)

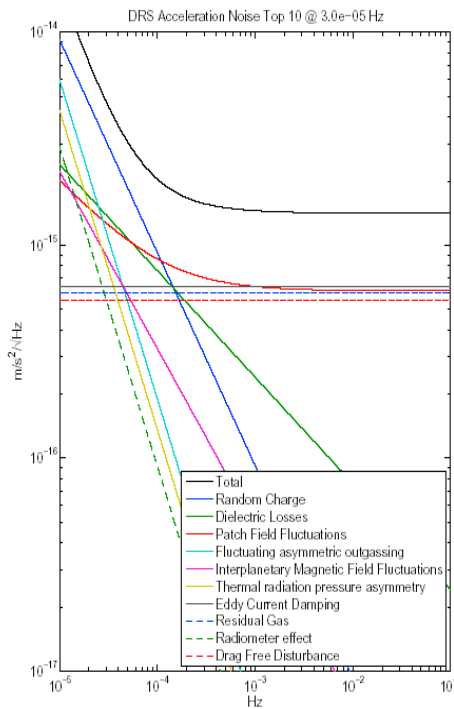


Figure 1: Acceleration-noise sources at 0.03mHz for LISA (Merkowitz 2006).

Electrical effects consume the bulk of the identified acceleration noises at low frequencies. Of these effects, the three most significant are random charging, dielectric losses, and voltage fluctuations. Charge on the proof mass couples to the residual DC electric field inside the GRS housing. Fluctuations in the proof mass charge, which result primarily from charging by cosmic-ray impacts and discharging by ultraviolet lamps,

represent the largest single contributor to the acceleration-noise budget at frequencies around 0.1 mHz and below. Dielectric losses on the electrode surfaces lead to force fluctuations through interactions with applied DC voltages. Fluctuations in the stray voltages due to surface potential differences (*i.e.*, time-varying “patch fields”) between each proof mass and its housing could be significant over these longer time scales. Fluctuations in the voltages applied to the electrode plates for position readout interact with charge on the proof masses, producing additional acceleration noise.

Thermal noise effects come in three primary varieties: radiation pressure, the so-called “radiometer” effect, and outgassing. All three of these are activated by fluctuations in the differential temperature across the proof mass. These cause fluctuations in the net momentum transfer by blackbody radiation from the housing. The radiometer effect, also known as thermal transpiration, arises from fluctuations in the thermal-induced pressure gradients in the gas surrounding each proof mass. Temperature fluctuations also cause variations in the outgassing rates of each proof mass and its housing, which in turn produce fluctuations in the residual gas pressure.

Another serious source of disturbance to the proof masses at very low frequencies arises from coupling to the fluctuating interplanetary magnetic field and to magnetic fields generated by the spacecraft. This coupling results from magnetic imperfections of the proof mass—*e.g.*, its nonzero magnetic susceptibility and residual magnetic dipole moment.

There exists a non-negligible “stiffness” between each proof mass and the surrounding spacecraft—that is, a collection of force-type disturbances on the proof masses that scale with fluctuations in the relative separation between the proof mass and its housing and surrounding spacecraft. Sensor readout errors, as well as back-action on the proof masses caused by actuation and by the thrusters used for drag-free control of the spacecraft, collectively produce significant levels of uncontrolled residual motion between the proof mass and its surroundings. Hence the stiffness must be understood, minimized, and estimated precisely in order to minimize these couplings. It is dominated by local gravitational gradients and electrostatic effects.

The specification regarding non-GW disturbances to the proof masses that must be satisfied as a necessary condition to achieving LISA's science goals is that the total acceleration noise on each proof mass not exceed  $3 \text{ fm/s}^2/\text{Hz}^{1/2}$  in LISA's measurement band below 3 millihertz (mHz). Above that frequency, this limit is relaxed somewhat, since precision at these higher frequencies is limited by other noise sources that affect the measurement of optical path delays. The noise requirement is usually stated as follows:

$$\sqrt{S_a} \leq 3 \times 10^{-15} \left[ 1 + \left( \frac{f}{3 \text{ mHz}} \right)^2 \right] \frac{\text{m}}{\text{s}^2} \frac{1}{\sqrt{\text{Hz}}}$$

for  $f \geq 0.1 \text{ mHz}$

To our knowledge this is the most challenging mechanical noise limit posited on any man-made object for any experiments performed at these low frequencies.

There are two important efforts underway to validate the acceleration-noise model of the LISA GRS: the LISA Pathfinder mission and ground-based torsion-balance tests.

The LISA Pathfinder mission (LPF) is designed as a technology demonstrator for LISA and was described in the May 2006 issue of *The LISA Newsletter*. LPF will carry two optically-coupled GRS systems, essentially a shortened version of one of the LISA arms. LPF will test the overall performance of the LISA GRS to within a factor smaller than 10 of the sensitivity required for LISA, and nearly approach LISA's required sensitivity at frequencies around 1 mHz and above. The success of LPF will substantially reduce the risk of failing to reach LISA's performance goals.

Despite the existence of LPF, laboratory tests to characterize LISA's "spurious" force disturbances and to identify any possible new issues must be pursued energetically, for a variety of reasons. Such tests have helped pave the way for LPF's success, by quantifying the performance gap that remains between LPF and LISA, and helping reduce it to its current factor of just below 10 for the anticipated effects. Laboratory tests are also critical to prepare for the interpretation of LISA Pathfinder results. Finally, at the lowest LISA measurement frequencies, close to 0.1 mHz, laboratory tests remain the only foreseeable tool to verify our noise models.

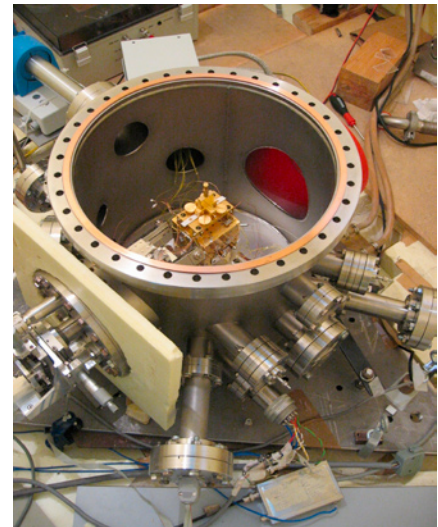
All ground-based laboratory tests being used currently to support LISA and LPF involve the use of torsion balances. Torsion balances can measure exquisitely small forces acting on macroscopic objects. With them we can simulate the dynamic conditions of space in certain degrees of freedom, *i.e.*, we can produce motion that is free from disturbing forces, including Earth's gravity. Two groups, one from the University of Trento and the other from the University of Washington, Seattle, have specialized in performing ground tests using torsion balances.

Since around 1998, the Trento group's program has focused on integrating the development and testing of the LISA GRS. They built a proof mass that is externally identical to a LISA proof mass but it is hollow, so that it can be suspended from a very thin torsion wire. The wire is made from tungsten, about 1 m long and 25  $\mu\text{m}$  in diameter. Since the wire is thin and long, it will be twisted by even very small torques. The resulting small angular motions are measurable using a highly sensitive angle readout system. The free torsional period of their pendulum is 560 s. Their pendulum is surrounded by a housing that is a functional replica of the capacitive sensing and actuation electrodes and of the housing for LISA's GRS. The system is designed to faithfully emulate the thermal and electrical environment that LISA's proof masses will experience in space.

The Trento group has used three setups: first a 40-mm proof mass with 2-mm gaps to the surrounding electrodes. This prototype had electrodes formed by a sandwich of ceramics and gold-coated molybdenum. A second setup (*Figure 2*) has been devoted to more closely emulate the final flight hardware, with a slightly larger test mass (46 mm) and with wider gaps (4 mm) in the laser-beam direction. The electrodes in this second prototype were formed by depositing gold directly onto a ceramic substrate embedded within the housing walls. A picture of this prototype, at different stages of integration inside the torsion-pendulum facility, is shown in *Figure 2*. A third setup (*Figure 3*) has the proof masses located at the ends of a horizontal bar that is carried by the torsion fiber. This latest setup is designed to be directly sensitive to forces, rather than torques. It is currently under preliminary commissioning, but its results are promising: at around 0.8 mHz, the force noise on the proof mass is  $< 200 \text{ fN}/\sqrt{\text{Hz}}$ , which converts for the 2-kg LISA proof-mass into an acceleration noise of  $< 100 \text{ fm-s}^{-2}/\sqrt{\text{Hz}}$ .

However, most of the work so far has been done with the simpler configurations, where the torsion wire is connected directly to the center of the proof mass. The primary quantity measured in this configuration is the torque about the fiber. However, simple conversion models allow us to extrapolate these results to infer upper limits on the equivalent acceleration noise that the 2-kg LISA proof masses would experience.

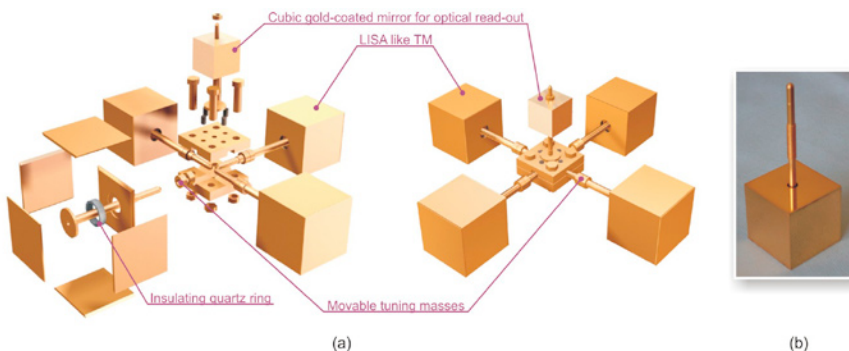
With these setups, the Trento group has gained experience that led to refined noise models for LISA. The largest concerns, regarding stray forces and cross couplings, were systematically addressed. The realistic nature of their test setup led to practical designs and maturity of the flight hardware for the LISA Pathfinder GRS.



**Figure 2:** The 46 mm test mass prototype integrated in the vacuum chamber of the torsion pendulum. Part of the micro-positioner used to center the electrode housing on the test mass is visible in the lower left part of the picture. On the upper left the optical angular readout is also visible.

Torsion-balance tests are inherently limited by the presence of thermal ("kT") torque noise generated within the torsion fiber. This noise depends on properties of the fiber. The torsion balance at Trento operates near this fundamental thermal-noise limit. The plot in *Figure 5* shows the upper limit on the acceleration-noise spectrum after known, measured noises specific to their test instrument, including the kT-fiber noise, have been subtracted. This upper limit includes all uncertainties of noise and model estimations.

**Figure 3:** Assembly drawing of the 4-proof mass pendulum at Trento. At right (b) is a photograph of one of the hollow proof-masses.



The group at the University of Washington in Seattle (UW) has in the past built some of the most sensitive torsion balances in the world, to conduct tests in gravity and fundamental physics. For LISA, Jens Gundlach and his collaborators have built their most sensitive instrument to date. Their setup does not look like a LISA GRS, but it is designed to maximize the ability to study small forces between adjacent surfaces.

In the tests at UW, the surface of the GRS housing is represented by their pendulum, which is a gold-coated silicon plate. This plate is very thin (0.45 mm), so that it can be supported by a fiber that is just 13 microns in diameter. The plate is also quite wide (10 cm), to increase the moment arm of the forces under investigation. The proof mass is represented by a gold-coated copper plate, which is placed parallel to the pendulum. To exaggerate surface forces, the separation between the two surfaces can be varied and made much smaller than the gaps planned for LISA. The UW experiments operate essentially at their kT-noise limit, which is lower than the Trento group's kT-limit. The dashed red line in *Figure 5* shows the upper limit on the excess, non-modeled noises related to surface effects in this configuration at a plate separation of 2 mm. This shows that there seem to be no unpredicted effects larger than this limit, such as fluctuations

of electrical potential, etc. between facing metal surfaces at millimeter distances.

Both the Trento and Seattle groups have studied individual acceleration-noise contributions. For example, by installing heaters on the mockups of the GRSs, thermal gradient effects were exaggerated and readily measured. Both groups found relatively good agreement with the LISA noise model (Carbone 2005).

At present, both groups are working to pin down the magnitudes of surface-potential fluctuations, a key input to the noise model (Schlamminger, 2006).

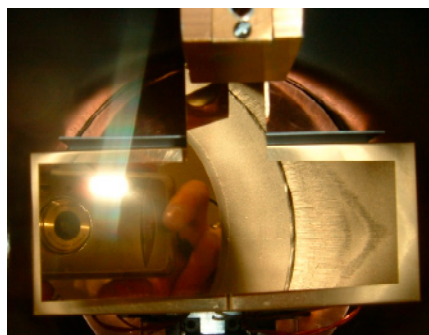
One of the most important conclusions from the torsion-balance ground tests is that at their present sensitivities, no show-stopping acceleration-noise sources have been discovered. In order to prove this with more certainty and in order to bridge the gap between the LPF and the LISA requirements, both groups are continuously upgrading their instruments so as to make more realistic and more sensitive tests.

It is interesting to note that the torsion balance, which was first used over 200 years ago to understand gravity, is now essential to prepare us for one of mankind's boldest

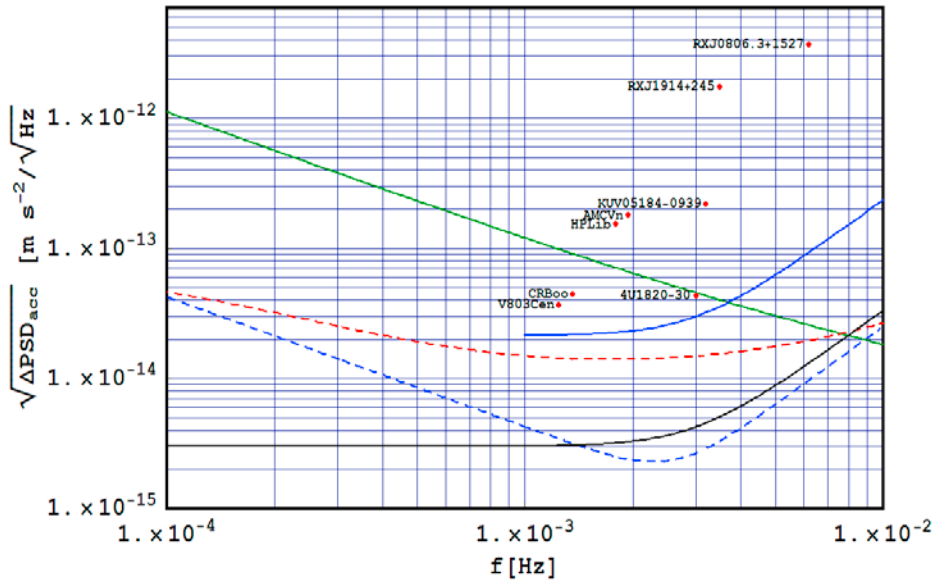
scientific endeavors, using gravity itself to observe the Universe.

### References:

- Carbone L 2005 "Ground based investigation of force noise sources for LISA" PhD Thesis, University of Trento
- Merkowitz S 2006 "Achieving the very low end of the LISA sensitivity band" in *Proceedings of the Sixth LISA Symposium*, AIP Conf Series
- Pollack S *et al.* 2006 "Outgassing, temperature gradients and the radiometer effect in LISA: A torsion pendulum investigation" in *Proceedings of the Sixth LISA Symposium*, AIP Conf Series
- Schlamminger S *et al.* 2006 "High sensitivity torsion balance tests for LISA" in *Proceedings of the Sixth LISA Symposium*, AIP Conf Series



**Figure 4:** Seattle surface-force setup. The shiny object (showing the reflection of the photographer) is a thin Au-coated silicon plate (GRS housing mock up) suspended from a 13- $\mu$ m thick tungsten torsion fiber next to a slightly larger Au-coated copper plate (proof-mass mock-up). This setup is optimized to measure small forces that arise between surfaces. In order to reach the sensitivity required for LISA the gap between the pendulum and the copper plate can be made much smaller than the gaps in the LISA GRS.



**Figure 5:** Upper limits on non-modeled surface effect related acceleration noise in LISA. Green solid line: upper limit from Trento pendulum measurements of a full GRS replica. Dashed red line: upper limit from high sensitivity Seattle torsion pendulum measurements using a gold-coated silicon plate.

Also shown are: LISA requirements (black solid line), LISA Pathfinder requirements (blue solid line), and LISA Pathfinder projected upper limit on all (surface and volume) non modeled forces (Dashed blue line). The red dots represent galactic binaries that would be seen with one year of integration if the corresponding acceleration noise level would be achieved in LISA.

## The Mock LISA data challenges

Stas Babak and Michele Vallisneri

for the Mock LISA Data Challenge Task Force

Mock data challenges are widely used in the development and validation of scientific experiments characterized by complex data flows, large collaborations, extensive use of information technology, and difficult or unproven data-analysis techniques. They involve the generation of mock data sets that impersonate the future output of measurements, at varying levels of realism. The data sets are then used to exercise select parts of the data collection and analysis chain. For example, a mock data challenge for a particle collider might be used to verify that the data storage system is fast enough to record all triggers, or to validate the statistical analysis of event backgrounds.

At the December 2005 meeting of the LISA International Science Team (LIST), the Data Analysis Working Group resolved to sponsor a series of Mock LISA Data Challenges (MLDCs) centered on LISA science data analysis, with dual purposes of encouraging early development of LISA-specific data-analysis methods and tools, and demonstrating the extent to which the gravitational-wave research community is technically ready to distill a rich science payoff from the LISA data output.

As described in detail in the LISA U.S. Mission Science Office’s “AMIGOS” planning document for the development of data-analysis methods [1], the MLDCs can also generate other useful byproducts. In the course of the challenges, the state of knowledge for specific types of analyses is inventoried, and idealized procedures are cast into forms that can be implemented in practice. Prototypes of software tools and architectures are created that may later evolve into production software or inform its design. And perhaps most important, a common data-analysis testing ground becomes available to all research groups, allowing them to compare approaches, exchange components, and verify each other’s results.

The MLDCs are organized in rounds of increasing complexity and realism, which are released and evaluated in sequence. Each round includes several data sets, which contain simulated LISA noise and gravitational waveforms from one or more expected LISA sources, with source parameters drawn randomly from plausible ranges. Each data set is distributed in two versions: a blind challenge set whose source parameters are not disclosed, and a training set with its source parameters provided (and, of course, different from those used in the challenge set).

Challenge participants are asked to respond with the maximum amount of information about the sources that they can extract from the challenge sets, and to provide a technical documentation of their work. One of the greatest scientific benefits of the challenges will come from quantitative comparisons of results, analysis methods, and implementations: thus, the challenges are truly blind tests, not contests, although a spirit of friendly competition can benefit scientific output.

An international MLDC task force, charged with administering the challenges, started work in February 2006. Its main responsibilities are the generation of challenge data sets and evaluation of challenge results. These involve several subtasks:

- Choosing the content of the challenge data sets, both gravitational-wave sources and instrument noise. These are chosen so as to target the specific aspects of LISA data analysis considered to present the major challenges. For example, one data set that has been chosen for the first round of challenges addresses the problem of detecting the signal from an isolated massive-black-hole (MBH) binary.

- Specifying data standards for the LISA sources. This includes selecting theoretical models for the waveforms (*e.g.*, black-hole binary inspirals are assumed to be circular and adiabatic, with radiation computed in the restricted 2PN approximation), and choosing standard sets of source parameters.
- Describing standard models for critical aspects of LISA, collectively called a “pseudo-LISA”, including such as things as the LISA orbits (*e.g.*, locations of LISA spacecraft at  $t=0$ ), instrument noise sources (*e.g.*, their spectra), and phase measurements (*e.g.*, choices for TDI combinations).
- Developing a standard file format to represent the data sets, with input–output libraries for several computational environments.
- Collecting or creating software to generate the gravitational waveforms and the pseudo-LISA instrument noise sources, and to assemble the LISA phase measurements and encode them in the standard format. All software is made available to the challengers, who can reproduce the MLDC pipelines to generate any number of additional training sets.
- Generating the challenge and training data sets, and storing the key files containing the answers to the challenges. The task of storing the answers is entrusted to two task force members who are sworn to secrecy and who will not take part in the MLDCs as challengers.
- Providing all participants in the MLDCs with any technical support required.

The MLDC task force was able to fulfill all of these tasks in time for the first round of challenge data sets to be presented to and endorsed by the LIST at their June 2006 meeting. Challenge-1 data sets were released publicly shortly thereafter; they are available online at [astrogravs.nasa.gov/docs/mldc](http://astrogravs.nasa.gov/docs/mldc). Results are due on or before 01 December 2006. They will be presented at the 11<sup>th</sup> Gravitational Wave Data Analysis Workshop (GWDAW11) in Golm, Germany later that month.

From the viewpoint of data analysis, these Challenge-1 problems are relatively easy. They focus on galactic binaries and massive black-hole inspirals—the GW sources considered high enough in priority to be retained even in a hypothetical minimum-

science LISA mission [2]. These sources are represented by simple, idealized theoretical waveforms, and the data sets do not include the “confusion background” of galactic white-dwarf binaries. This simplification has allowed the task force to concentrate first on the development of the basic tools and common conventions that will be used for subsequent, more complex challenges. It also gives the competing research groups time to learn and understand the tools and conventions without the added complexity of more realistic waveforms.

Challenge-2 data sets will be released at December’s GWDAW11, with results due back to the task force in June 2007. Training sets for Challenge 2 will be released earlier as they become available. Challenge 2 will focus on data sets characterized by many overlapping and interfering GW signals from multiple source types. This is known as the “global-fit problem” of LISA data analysis. When sources overlap like this in the time and frequency domains, it can become difficult or impossible to distinguish them without skewing estimates of their parameters. A strong signal may even obscure a weaker signal entirely. Challenge-2 data sets will include radiation from a background of about 30,000 galactic binaries, with parameters drawn from population-synthesis simulations. Extreme-mass-ratio inspirals will also be featured more prominently in this second round.

The third round of challenges will be released in June 2007 for evaluation the following December, and the fourth in December 2007 for evaluation in June 2008. The content for these data sets has not been decided yet, but they will include additional LISA sources such as bursts and stochastic backgrounds, as well as more realistic models of instrument noise and operation (*e.g.*, noise nonstationarity, data gaps and disturbances, etc.).

We encourage all interested groups and individuals to take part in the mock LISA data challenges. Participants should subscribe to the MLDC challenge mailing list ([gravity.psu.edu/mailman/listinfo/lisatools-challenge](mailto:gravity.psu.edu/mailman/listinfo/lisatools-challenge)) and register with one of the MLDC task force co-chairs (Michele Vallisneri at [vallis@caltech.edu](mailto:vallis@caltech.edu) or Alberto Vecchio at [av@star.sr.bham.ac.uk](mailto:av@star.sr.bham.ac.uk)). The standards, conventions, and signal-generation pipelines used to generate Challenge-1 data sets are documented extensively in the Challenge-1 omnibus document [3]. The

activities of the task force can be tracked at their wiki ([tapir.caltech.edu/dokuwiki/list-wg1b:home](http://tapir.caltech.edu/dokuwiki/list-wg1b:home)), while the MLDC software is collected in the LISAtools SourceForge project ([sourceforge.net/projects/lisatools](http://sourceforge.net/projects/lisatools)), which also hosts documentation, bug tracking, and user forums.

We are very excited about the progress and results to date of the MLDC effort, and are confident that it will help bring together research groups from around the world working on LISA data analysis. It will serve as an excellent first step toward coordinating international efforts in this area, and ultimately toward advancing the leading edge of LISA scientific research and demonstrating its full potential.

## References

- Prince T, *et al.* 2005 “Analysis methods for Interferometric Gravitational-wave Observations from space (AMIGOS): NASA Development Plan for the LISA Mission v0.2” [www.srl.caltech.edu/lisa/LIST\\_meetings/LIST\\_dec05/AMIGOS-DP-v0.2-20051209.pdf](http://www.srl.caltech.edu/lisa/LIST_meetings/LIST_dec05/AMIGOS-DP-v0.2-20051209.pdf)
- Prince T, Danzmann K 2005 “LISA Science Requirements Document v3.0” [www.srl.caltech.edu/lisa/documents](http://www.srl.caltech.edu/lisa/documents)
- Mock LISA Data Challenge Task Force 2006 “Document for Challenge 1” [svn.sourceforge.net/viewvc/lisatools/Docs/challenge1.pdf](http://svn.sourceforge.net/viewvc/lisatools/Docs/challenge1.pdf)

The Sixth International LISA Symposium was held June 19-23, 2006, at NASA Goddard Space Flight Center in Greenbelt, Maryland. It was locally organized by scientists from Goddard and the University of Maryland. More than 200 people attended from 34 countries and 90 institutions. The Symposium was sponsored by the LISA Project along with a grant from the National Science Foundation that supported a fair number of the attending students.

The LISA community has grown considerably since the first LISA Symposium held twelve years ago at Rutherford Appleton Laboratory. Since then, the LISA Project entered its Formulation phase and the LISA Pathfinder mission started building flight hardware. At the same time, ground-based gravitational-wave antennas have made great strides, with several resonant detectors in continuous operation and the large-scale interferometers operating near design sensitivity.

The Sixth International LISA Symposium began with a pre-program tutorial session to introduce newcomers to the astrophysics, data analysis and design of the LISA mission. The tutorials were followed by a welcoming address by Colleen Hartman, the Deputy Associate Administrator for NASA's Science Mission Directorate who gave an overview of NASA's science program and answered questions on the future of the Beyond Einstein Program. The rest of the first day was dedicated to overview talks on the science of LISA as well as the status of the LISA mission, LISA Pathfinder, and ground-based gravitational wave antennas. Each of the next three days (Tuesday through Thursday) was organized around a theme based on the LISA gravitational-wave sources. Talks about the LISA instrument were chosen to address the measurement frequency band of primary importance for the science source being discussed that day. Overview talks were given in the mornings to set the stage for the focused afternoon talks.

Tuesday's theme was *Central Massive Black Holes, Cosmological Implications, and the Very-Low End of the LISA Sensitivity Band*. The day began with Marta Volonteri and Steinn Sigurdsson describing how mergers of massive black holes produce some of the strongest signals LISA will observe, and how they can be used to probe cosmological evolution. Several presentations then described recent breakthroughs

in numerical relativity, and how we are now able to predict the full evolution and gravitational waveforms associated with these mergers. Numerical relativists succeeded in using supercomputers to compute the waveforms associated with the highly relativistic coalescence of black-hole binaries. This work marked the first successful joining of previously known waveforms for the inspiral phase (when the two black holes are still separated by many radii) and the post-merger ring-down phase of the resulting composite black hole.

A number of groups then gave presentations discussing LISA performance at measurement frequencies around 0.1 mHz and below. Measurement capability at these low frequencies will enable better distance estimates and angular resolution of massive-black-hole mergers, as well as detection of more of these intriguing and powerful gravitational-wave sources. The limit to measurement sensitivity in this regime comes from acceleration disturbances to the LISA proof masses. The University of Washington group described its experiments with a sensitive torsion pendulum to study and characterize some of the most challenging disturbance effects. The University of Trento group showed how their torsion pendulum has been used to characterize the performance of the LISA Pathfinder gravitational reference sensor. No unexpected disturbances have been found to date that would severely limit its sensitivity at very low frequencies. The Imperial College group brought us up to date on proof-mass charging effects and designs for a system to manage charge build-up on the proof masses. Effective charge management is essential to achieving low-frequency measurement sensitivity as the associated electrostatic disturbances rise sharply and become dominant at low frequencies.

At a banquet held Tuesday evening, John Mather gave a talk about his experience on the COBE mission. He described how the COBE team was able to overcome some very challenging obstacles and disasters, and encouraged the LISA team to take heart that with perseverance we will successfully overcome the challenges we face.

Wednesday's theme was *Dynamics around a Central Black Hole and the Mid-High End of the LISA Sensitivity Band*. The day began with Scott Hughes and Clovis Hopman discussing the astrophysics to be learned from gravitational observations of

extreme-mass-ratio inspirals (EMRIs), as well as how they can be used to test General Relativity. EMRI sources produce gravitational waves in the mid-to-high end of the LISA measurement band, where optical-path length measurement noise (as opposed to proof-mass disturbances) limits instrument sensitivity. Gerhard Heinzel and Daniel Shaddock introduced the instrument talks by explaining the way LISA's interferometric measurement is divided into a long arm (spacecraft to spacecraft) and a short arm (spacecraft to proof mass). The afternoon talks reviewed progress in developing the LISA optical design as well as construction of the LISA Pathfinder optical bench. Rachel Cruz described the University of Florida's laboratory demonstration of Time Delay Interferometry, a technique used to process LISA's interferometric phase measurements that is crucial for suppressing the contribution of laser phase noise to the LISA data.

Thursday's theme was *Stellar-Mass Binaries, Stochastic Sources, and the Mid-Low End of the LISA Sensitivity Band*. Gijs Nelemans and Chris Belczynski opened discussions by describing how LISA will detect gravitational-wave signals from the huge populations of white-dwarf and neutron-star binaries in our Milky Way Galaxy. The population of galactic white dwarf binaries is much better known now than it was a few years ago. Estimates of the gravitational-wave "confusion background" from these have not changed much in recent years, primarily due to previous underestimates of their spatial density and overestimates of their masses. However, mysteries regarding these sources remain. Two such systems were found that have short periods consistent with expectations, but the rates of change of their periods do not have the expected sign. Patrick Motl presented results from simulations of mass transfer in double white-dwarf binary systems which demonstrate that it is possible for binary systems to survive even if they have mass ratios that would make the mass transfer initially unstable. Jeremy Schnittman described a scenario by which star formation could be triggered in the disks around active galactic nuclei (AGNs). This mechanism could produce a population of compact objects that would result in an identifiable subset of EMRIs as these objects were captured by the central massive black-hole engine of the AGN. This work will help us improve estimates of event rates for these LISA sources. Several talks on science data analysis de-

scribed techniques that have been used to demonstrate successful extractions of individual gravitational-wave signals from simulated data sets containing many binaries within a small frequency band. Neil Cornish concluded that computing requirements for sorting out multiple LISA signals spaced closely in frequency do not appear to be a limitation for science data analysis except for the extreme case of identifying inspirals of smaller objects (small black holes, neutron stars, white dwarfs) into much more massive black holes in galactic nuclei. Shane Larson described the difficulties that arise when comparing results associated with different data-analysis algorithms, and why no single technique will be best suited to answer all questions posed to the science data.

Stefano Vitale gave an overview of the expected acceleration disturbances to the proof masses, with convincing evidence that they now appear to be well understood. The development of the gravitational reference sensor for the LISA Pathfinder and laboratory measurements using torsion

pendulums were critical in gaining this understanding. In the past year, better limits on the forces from energy dissipation due to electrical fields have been established, and acceptable performance of active compensation for variations in work functions on the electrodes was demonstrated with good precision. Peiman Maghami described the now-completed drag-free control design for ST7 and verification of its performance and stability by high-fidelity simulations. John Ziemer and Cesar Garcia-Marirrodriga presented the excellent progress that has been made developing micronewton thrusters, particularly in the area of improving and demonstrating lifetime.

The final day of the Symposium (Friday) began with a forward-looking talk by Craig Hogan about new physics with LISA. This was followed by parallel sessions on data analysis and on LISA systems and technology. The data-analysis session was abuzz with discussions of the ongoing mock LISA data challenge. The systems and technology session described a host of lessons learned from the LISA Pathfinder development as

well as the excellent progress made in developing the LISA phasemeters.

Many outstanding presentations were given over the course of the week. There were a total of 71 technical talks given and nearly 70 posters displayed. Copies of the presentations and posters are available for download from the Symposium website: [lisa6.gsfc.nasa.gov/](http://lisa6.gsfc.nasa.gov/). The Symposium proceedings will be published by the American Institute of Physics before the end of this year. It will contain 105 articles spanning almost 700 pages.

The LISA Symposium successfully brought together scientists and engineers working on all aspects of the LISA mission, from data analysts and source modelers to hardware developers. NASA Goddard Space Flight Center provided an ideal environment for the exchange of ideas between colleagues. The quality of the presentations, diversity of the participants, and excellent logistical support all contributed to making this symposium a complete success.



Titles, authors, preprint reference, and abstracts are given below for some of the exciting LISA-relevant publications from the past several months.

## 1. [gr-qc/0607007]

*“Kludge” gravitational waveforms for a test-body orbiting a Kerr black hole*

Stanislav Babak, Hua Fang, Jonathan R. Gair, Kostas Glampedakis, Scott A. Hughes

03 Jul 2006

**Abstract:** One of the most exciting potential sources of gravitational waves for low-frequency, space-based gravitational wave (GW) detectors such as the proposed Laser Interferometer Space Antenna (LISA) is the inspiral of compact objects into massive black holes in the centers of galaxies. The detection of waves from such “extreme mass ratio inspiral” systems (EMRIs) and extraction of information from those waves require template waveforms. The systems’ extreme mass ratio means that their waveforms can be determined accurately using black hole perturbation theory. Such calculations are computationally very expensive. There is a pressing need for families of approximate waveforms that may be generated cheaply and quickly but which still capture the main features of true waveforms. In this paper, we introduce a family of such “kludge” waveforms and describe ways to generate them. We assess performance of the introduced approximations by comparing “kludge” waveforms to accurate waveforms obtained by solving the Teukolsky equation in the adiabatic limit (neglecting GW back-reaction). We find that the kludge waveforms do extremely well at approximating the true gravitational waveform, having overlaps with the Teukolsky waveforms of 95% or higher over most of the parameter space for which comparisons can currently be made. Indeed, we find these kludges to be of such high quality (despite their ease of calculation) that it is possible they may play some role in the final search of LISA data for EMRIs.

## 2. [astro-ph/0606601]

*Gravity’s Relentless Pull: An interactive, multimedia website about black holes for Education and Public Outreach*

Roeland P van der Marel (STScI), David Schaller (EduWeb), Gijs Verdoes Kleijn (Groningen Univ.)

23 Jun 2006

**Abstract:** We have created a website, called “Black Holes: Gravity’s Relentless Pull”, which explains the physics and astronomy

of black holes for a general audience. The site emphasizes user participation and is rich in animations and astronomical imagery. It won the top prize of the 2005 Pirelli INTERNATIONAL Awards competition for the best communication of science and technology using the internet. This article provides a brief overview of the site. The site starts with an opening animation that introduces the basic concept of a black hole. The user is then invited to embark on a journey from a backyard view of the night sky to a personal encounter with a singularity. This journey proceeds through three modules, which allow the user to: find black holes in the night sky; travel to a black hole in an animated starship; and explore a black hole from up close. There are also five “experiments” that allow the user to: create a black hole; orbit around a black hole; weigh a black hole; drop a clock into a black hole; or fall into a black hole. The modules and experiments offer goal-based scenarios tailored for novices and children. The site also contains an encyclopedia of frequently asked questions and a detailed glossary targeted more at experts and adults. The overall result is a website where scientific knowledge, learning theory, and fun converge. Despite its focus on black holes, the site also teaches many other concepts of physics, astronomy and scientific thought. The site aims to instill an appreciation for learning and an interest in science, especially in the younger users. It can be used as an aid in teaching introductory astronomy at the undergraduate level.

## 3. [astro-ph/0606427]

*Capture Rates of Compact Objects by Supermassive Black Holes*

José Antonio de Freitas Pacheco, Charline Filloux, Tania Regimbau

18 Jun 2006

**Abstract:** Capture rates of compact objects were calculated by using a recent solution of the Fokker-Planck equation in energy-space, including two-body resonant effects. The fraction of compact objects (white dwarfs, neutron stars and stellar black holes) was estimated as a function of the luminosity of the galaxy from a new grid of evolutionary models. Stellar mass densities at the influence radius of central supermassive black holes were derived from brightness profiles obtained by Hubble Space Telescope observations. The present study indicates that the capture rates scale as  $\propto M_{\text{bh}}^{-1.048}$ , consequence of the fact that dwarf galaxies have denser central regions than luminous objects. If the mass distribution of supermassive black holes has a lower cutoff at

$\sim 1.4 \times 10^6 M_{\odot}$  (corresponding to the lowest observed supermassive black-hole mass, located in M32), then 9 inspiral events are expected to be seen by LISA (7-8 corresponding to white dwarf captures and 1-2 to neutron star and stellar black hole captures) after one year of operation. However, if the mass distribution extends down to  $\sim 2 \times 10^5 M_{\odot}$ , then the total number of expected events increases up to 579 (corresponding to  $\sim 274$  stellar black hole captures,  $\sim 194$  neutron star captures and  $\sim 111$  white dwarf captures).

## 4. [gr-qc/0604115]

*Strategies for observing extreme mass ratio inspirals*

Steve Drasco

26 Aug 2006

**Abstract:** I review the status of research, conducted by a variety of independent groups, aimed at the eventual observation of Extreme Mass Ratio Inspirals (EMRIs) with gravitational wave detectors. EMRIs are binary systems in which one of the objects is much more massive than the other, and which are in a state of dynamical evolution that is dominated by the effects of gravitational radiation. Although these systems are highly relativistic, with the smaller object moving relative to the larger at nearly light-speed, they are well described by perturbative calculations which exploit the mass ratio as a natural small parameter. I review the use of such approximations to generate waveforms needed by data analysis algorithms for observation. I also briefly review the status of developing the data analysis algorithms themselves. Although this article is almost entirely a review of previous work, it includes (as an appendix) a new analytical estimate for the time over which the influence of radiation on the binary itself is observationally negligible.

## 5. [astro-ph/0608460]

(a LISA6 proceeding)

*Astrophysics of extreme mass ratio inspiral sources*

Clovis Hopman (Leiden Observatory)

22 Aug 2006

**Abstract:** Compact remnants on orbits with peri-apses close to the Schwarzschild radius of a massive black hole (MBH) lose orbital energy by emitting gravitational waves (GWs) and spiral in. Scattering with other stars allows successful inspiral of such extreme mass ratio inspiral sources (EMRIs) only within small distances,  $a < \text{few} \times 0.01$  pc from the MBH. The event rate of EMRIs is therefore dominated by the stellar dynamics

and content in the inner few  $\times 0.01$  pc. I discuss the relevant dynamical aspects and resulting estimated event rates of EMRIs. Subjects considered include the loss-cone treatment of inspiral sources; mass segregation; resonant relaxation; and alternative routes to EMRI formation such as tidal binary disruptions, stellar formation in disks and tidal capture of massive main sequence stars. The EMRI event rate is estimated to be of order few  $\times 10^2 \text{Gyr}^{-1}$  per MBH, giving excellent prospects for observation by LISA.

#### 6. [gr-qc/0608112]

*Slice & Dice: Identifying and Removing Bright Galactic Binaries from LISA Data*

Louis J. Rubbo, Neil J. Cornish, Ronald W. Hellings

25 Aug 2006

**Abstract:** Here we describe a hierarchical and iterative data analysis algorithm used for searching, characterizing, and removing bright, monochromatic binaries from the Laser Interferometer Space Antenna (LISA) data streams. The algorithm uses the  $\mathcal{F}$ -statistic to provide an initial solution for individual bright sources, followed by an iterative least squares fitting for all the bright sources. Using the above algorithm, referred to as Slice & Dice, we demonstrate the removal of multiple, correlated galactic binaries from simulated LISA data. Initial results indicate that Slice & Dice may be a useful tool for analyzing the forthcoming LISA data.

#### 7. [gr-qc/0608062]

*Measuring coalescing massive binary black holes with gravitational waves: The impact of spin-induced precession*

Ryan N. Lang, Scott A. Hughes

11 Aug 2006

**Abstract:** The coalescence of massive black holes generates gravitational waves (GWs) that will be measurable by space-based detectors such as LISA to large redshifts. The spins of a binary's black holes have an important impact on its waveform. Specifically, geodetic and gravitomagnetic effects cause the spins to precess; this precession then modulates the waveform, adding periodic structure which encodes useful information about the binary's members. Following pioneering work by Vecchio, we examine the impact upon GW measurements of including these precession-induced modulations in the waveform model. We find that the additional periodicity due to spin precession breaks degeneracies among certain parameters, greatly improving the accuracy with which they may be

measured. In particular, mass measurements are improved tremendously, by one to several orders of magnitude. Localization of the source on the sky is also improved, though not as much—low redshift systems can be localized to an ellipse which is roughly  $10 - \text{a few } \times 10$  arcminutes in the long direction and a factor of  $2 - 5$  smaller in the short direction. Though not a drastic improvement relative to analyses which neglect spin precession, even modest gains in source localization will greatly facilitate searches for electromagnetic counterparts to GW events. Determination of distance to the source is likewise improved: We find that relative error in measured luminosity distance is commonly  $\sim 0.1 - 0.4\%$  at  $z \sim 1$ . Finally, with the inclusion of precession, we find that the magnitude of the spins themselves can typically be determined for low redshift systems with an accuracy of about  $0.1 - 10\%$ , depending on the spin value, allowing accurate surveys of mass and spin evolution over cosmic time.

#### 8. [astro-ph/0609504]

*Prospects for direct detection of circular polarization of gravitational-wave background*

Naoki Seto

18 Sep 2006

**Abstract:** We discussed prospects for directly detecting circular polarization signal of gravitational wave background. We found it is generally difficult to probe the monopole mode of the signal due to broad directivity of gravitational wave detectors. But the dipole ( $l=1$ ) and octupole ( $l=3$ ) modes of the signal can be measured in a simple manner by combining outputs of two unaligned detectors, and we can dig them deeply under confusion and detector noises. Around  $f \sim 0.1 \text{mHz}$  LISA will provide ideal data streams to detect these anisotropic components whose magnitudes are as small as  $\sim 1$  percent of the detector noise level in terms of the non-dimensional energy density  $\Omega_{\text{GW}}(f)$ .

#### 9. [astro-ph/0609172]

*The Final Merger of Comparable Mass Binary Black Holes (a LISA6 proceeding)*

Joan M. Centrella

06 Sep 2006

**Abstract:** A remarkable series of breakthroughs in numerical relativity modeling of black-hole binary mergers has occurred over the past few years. This paper provides a general overview of these exciting developments, focusing on recent progress in merger simulations and calculations of the resulting gravitational waveforms.

#### 10. [gr-qc/0609028]

*A brief survey of LISA sources and science (a LISA6 proceeding)*

Scott A. Hughes

07 Sep 2006

**Abstract:** LISA is a planned space-based gravitational-wave (GW) detector that would be sensitive to waves from low-frequency sources, in the band of roughly  $(0.03 - 0.1) \text{mHz} \leq f \leq 0.1 \text{Hz}$ . This is expected to be an extremely rich chunk of the GW spectrum—observing these waves will provide a unique view of dynamical processes in astrophysics. Here we give a quick survey of some key LISA sources and what GWs can uniquely teach us about these sources. Particularly noteworthy science which is highlighted here is the potential for LISA to track the moderate-to-high redshift evolution of black hole masses and spins through the measurement of GWs generated from massive black hole binaries (which in turn form by the merger of galaxies and protogalaxies). Measurement of these binary black hole waves has the potential to determine the masses and spins of the constituent black holes with percent-level accuracy or better, providing a unique high-precision probe of an aspect of early structure growth. This article is based on the 'Astrophysics Tutorial' talk given by the author at the Sixth International LISA Symposium.

#### 11. [gr-qc/0609010]

*Automatic Bayesian inference for LISA data analysis strategies*

Alexander Stroeer, Jonathan Gair, Alberto Vecchio

04 Sep 2006

**Abstract:** We demonstrate the use of automatic Bayesian inference for the analysis of LISA data sets. In particular we describe a new automatic Reversible Jump Markov Chain Monte Carlo method to evaluate the posterior probability density functions of the *a priori* unknown number of parameters that describe the gravitational wave signals present in the data. We apply the algorithm to a simulated LISA data set containing overlapping signals from white dwarf binary systems (DWD) and to a separate data set containing a signal from an extreme mass ratio inspiral (EMRI). We demonstrate that the approach works well in both cases and can be regarded as a viable approach to tackle LISA data analysis challenges.

**12. [gr-qc/0608140]***(Sort of) Testing relativity with extreme mass ratio inspirals*

Scott A. Hughes

31 Aug 2006

**Abstract:** The inspirals of ‘small’ ( $1 - 100 M_{\odot}$ ) compact bodies through highly relativistic orbits of massive (several  $\times 10^5 M_{\odot}$  – several  $\times 10^6 M_{\odot}$ ) black holes are among the most anticipated sources for the LISA gravitational-wave antenna. The measurement of these waves is expected to map the spacetime of the larger body with high precision, allowing us to test in detail the hypothesis that black hole candidates are described by the Kerr metric of general relativity. In this article, we will briefly describe how these sources can be used to perform such a test. These proposed measurements are often described as ‘testing relativity’. This description is at best somewhat glib: Because—at least to date—all work related to these measurements assumes general relativity as the theoretical framework in which these tests are performed, the measurements cannot be said to ‘test relativity’ in a fundamental way. More accurately, they test the *nature of massive compact bodies within general relativity*. A surprising result for such a test could point to deviations from general relativity, and would provide an experimentally motivated direction in which to pursue tests of gravity theories beyond GR.

**13. [gr-qc/0608138]***Optimal Source Tracking and Beaming of LISA (a LISA6 proceeding)*

Archana Pai

31 Aug 2006

**Abstract:** We revisit the directionally optimal data streams of LISA first introduced in Nayak et al. It was shown that by using appropriate choice of Time delay interferometric (TDI) combinations, a monochromatic fixed source in the barycentric frame can be optimally tracked in the LISA frame. In this work, we study the beaming properties of these optimal streams. We show that all the three streams  $V_+$ ,  $V_x$  and  $V_0$  with maximum, minimum and zero directional SNR respectively are highly beamed. We study in detail the frequency dependence of the beaming.

**14. [gr-qc/0610139]***Accurate and efficient gravitational waveforms for certain galactic compact binaries*

Manuel Tessmer, Achamveedu Gopakumar

27 Oct 2006

**Abstract:** Stellar-mass compact binaries in eccentric orbits are almost guaranteed

sources of gravitational waves for Laser Interferometer Space Antenna. We present a prescription to compute accurate and efficient gravitational-wave polarizations associated with bound compact binaries of arbitrary eccentricity and mass ratio moving in slowly precessing orbits. We compare our approach with those existing in the literature and present its advantages.

**15. [gr-qc/0610117]***Isolation of gravitational waves from displacement noise and utility of a time-delay device*

Kentaro Somiya, Keisuke Goda, Yanbei Chen, Eugeny E. Mikhailov

25 Oct 2006

**Abstract:** Interferometers with kilometer-scale arms have been built for gravitational-wave detections on the ground; ones with much longer arms are being planned for space-based detection. One fundamental motivation for long baseline interferometry is from displacement noise. In general, the longer the arm length  $L$ , the larger the motion the gravitational wave induces on the test masses, until  $L$  becomes comparable to the gravitational wavelength. Recently, schemes have been invented, in which displacement noises can be evaded by employing differences between the influence of test-mass motions and that of gravitational waves on light propagation. However, in these schemes, such differences only become significant when  $L$  approaches the gravitational wavelength, and shot-noise limited sensitivity becomes worse than that of conventional configurations by a factor of at least  $(fL/c)^{-2}$ , for  $f < c/L$ . Such a factor, although can be overcome theoretically by employing high optical powers, makes these schemes quite impractical. In this paper, we explore the use of time delay in displacement-noise-free interferometers, which can improve their shot-noise-limited sensitivity at low frequencies, to a factor of  $(fL/c)^{-1}$  of the shot-noise-limited sensitivity of conventional configurations.

**16. [gr-qc/0610122]***Inspiral, merger and ring-down of equal-mass black-hole binaries*

Alessandra Buonanno, Gregory B. Cook, Frans Pretorius

25 Oct 2006

**Abstract:** We investigate the dynamics and gravitational-wave (GW) emission in the binary merger of equal-mass black holes as obtained from numerical relativity simulations. Results from the evolution of three sets of initial data are explored in detail, corresponding to different initial separa-

tions of the black holes. We find that to a good approximation the inspiral phase of the evolution is quasi-circular, followed by a “blurred, quasi-circular plunge”, then merger and ring down. We present first-order comparisons between analytical models of the various stages of the merger and the numerical results. We provide comparisons between the numerical results and analytical predictions based on the adiabatic Newtonian, post-Newtonian (PN), and non-adiabatic resummed-PN models. From the ring-down portion of the GW we extract the fundamental quasi-normal mode and several of the overtones. Finally, we estimate the optimal signal-to-noise ratio for typical binaries detectable by GW experiments.

**17. [astro-ph/0610657]***Black-Hole Phenomenology*

Neven Bilic

23 Oct 2006

**Abstract:** This set of lectures is an introduction to black-hole astrophysics. The emphasis is made on the phenomenology of X-ray binaries and of supermassive compact objects at galactic centers.

**18. [astro-ph/0610680]***Gravitational-wave background from compact objects embedded in AGN accretion disks*

Guenther Sigl, Jeremy Schnittman, Alessandra Buonanno

23 Oct 2006

**Abstract:** We consider a model in which massive stars form in a self-gravitating accretion disk around an active galactic nucleus (AGN). These stars may evolve and collapse to form compact objects on a time scale shorter than the accretion time, thus producing an important family of sources for LISA. Assuming the compact object formation/inspiral rate is proportional to the steady-state gas accretion rate, we use the intrinsic hard X-ray AGN luminosity function to estimate expected event rates and signal strengths. We find that these sources will produce a continuous low-frequency ( $\approx 1$  mHz) background detectable by LISA if more than  $\sim 1\%$  of the accreted matter is in the form of compact objects. For compact objects with masses  $\geq 10$  solar masses, the last stages of the inspiral events should be resolvable above a few mHz, with rates as high as a few hundred per year.

**19. [astro-ph/0610478]**

*Intermediate-mass black holes in colliding clusters: Implications for lower-frequency gravitational-wave astronomy*

Pau Amaro-Seoane, Marc Freitag

16 Oct 2006

**Abstract:** Observations suggest that star clusters often form in binaries or larger bound groups. Therefore, mergers between two clusters are likely to occur. If these clusters both harbor an intermediate-mass black hole (IMBH;  $\sim 10^{2-4} M_{\odot}$ ) in their center, they can become a strong source of gravitational waves when the black holes merge with each other. In order to understand the dynamical processes that operate in such a scenario, one has to study the evolution of the merger of two such young massive star clusters, and more specifically, their respective IMBHs. We employ the direct-summation Nbody4 numerical tool on special-purpose GRAPE6 hardware to simulate a merger of two stellar clusters each containing 63,000 particles and a central IMBH. This allows us to study accurately the orbital evolution of the colliding clusters and the embedded massive black holes. Within  $\sim 7$  Myr the clusters have merged and the IMBHs constitute a hard binary. The final coalescence happens in  $\sim 10^8$  yrs. The implication of our analysis is that intermediate-mass black holes merging as the result of coalescence of young dense clusters could provide a source for the Laser Interferometer Space Antenna (LISA) space-based gravitational wave detector mission. We find that interactions with stars increase the eccentricity of the IMBH binary to about 0.8. Although the binary later circularizes by emission of gravitational waves, the residual eccentricity can be detectable through its influence on the phase of the waves if the last few years of inspiral are observed.

**20. [gr-qc/0610046]**

*Detecting extreme mass ratio inspiral events in LISA data using the Hierarchical Algorithm for Clusters and Ridges (HACR)*

Jonathan R Gair, Gareth Jones

10 Oct 2006

**Abstract:** One of the most exciting prospects for the Laser Interferometer Space Antenna (LISA) is the detection of gravitational waves from the inspirals of stellar-mass compact objects into supermassive black holes. Detection of these sources is an extremely challenging computational problem due to the large parameter space and low amplitude of the signals. However, recent work has suggested that the nearest extreme mass ratio inspiral (EMRI) events

will be sufficiently loud that they might be detected using computationally cheap, template-free techniques, such as a time-frequency analysis. In this paper, we examine a particular time-frequency algorithm, the Hierarchical Algorithm for Clusters and Ridges (HACR). This algorithm searches for clusters in a power map and uses the properties of those clusters to identify signals in the data. We find that HACR applied to the raw spectrogram performs poorly, but when the data is binned during the construction of the spectrogram, the algorithm can detect typical EMRI events at distances of up to  $\sim 2.5$ Gpc. This is a little further than the simple Excess Power method that has been considered previously. We discuss the HACR algorithm, including tuning for single and multiple sources, and illustrate its performance for detection of typical EMRI events, and other likely LISA sources, such as white dwarf binaries and supermassive black hole mergers. We also discuss how HACR cluster properties can be used for parameter extraction.

**21. [astro-ph/0611546]**

*A Solution to the Galactic Foreground Problem for LISA*

Jeff Crowder, Neil Cornish

17 Nov 2006

**Abstract:** Low frequency gravitational wave detectors, such as the Laser Interferometer Space Antenna (LISA), will have to contend with large foregrounds produced by millions of compact galactic binaries in our galaxy. While these galactic signals are interesting in their own right, the unresolved component can obscure other sources. The science yield for the LISA mission can be improved if the brighter and more isolated foreground sources can be identified and regressed from the data. Since the signals overlap with one another we are faced with a “cocktail party” problem of picking out individual conversations in a crowded room. Here we present and implement an end-to-end solution to the galactic foreground problem that is able to resolve tens of thousands of sources from across the LISA band. Our algorithm employs a variant of the Markov Chain Monte Carlo (MCMC) method, which we call the Blocked Annealed Metropolis-Hastings (BAM) algorithm. Following a description of the algorithm and its implementation, we give several examples ranging from searches for a single source to searches for hundreds of overlapping sources. Our examples include data sets from the first round of Mock LISA Data Challenges.

**22. [astro-ph/0611110]**

*Gravitational recoil velocities from eccentric binary black hole mergers*

Carlos F. Sopuerta, Nicolas Yunes, Pablo Laguna

3 Nov 2006

**Abstract:** The formation and growth of supermassive black holes is a key issue to unveil the secrets of galaxy formation. In particular, the gravitational recoil produced in the merger of unequal mass black hole binaries could have a number of astrophysical implications, such as the ejection of black holes from the host galaxy or globular cluster. We present estimates of the recoil velocity that include the effect of small eccentricities. The approach is specially suited for the last stage of the merger, where most of the emission of linear momentum in gravitational waves takes place. Supplementing our estimates with post-Newtonian approximations, we obtain lower and upper bounds that constrain previous recoil velocities estimates as well as a best estimate that agrees with numerical simulations in the quasi-circular case. For eccentricities  $e \leq 0.1$ , the maximum recoil is found for mass ratios of  $M_1/M_2 \sim 0.38$  with a best estimate of  $\sim 167(1+e)$  km  $s^{-1}$  and upper and lower bounds of  $79(1+e)$  km  $s^{-1}$  and  $216(1+e)$  km  $s^{-1}$  respectively.

**23. [gr-qc/0611039]**

*Multipole moments as a tool to infer from gravitational waves the geometry around an axisymmetric body*

Thomas P. Sotiriou, Theodoros A. Apostolatos

6 Nov 2006

**Abstract:** A binary system, composed of a compact object orbiting around a massive central body, will emit gravitational waves which will depend on the central body’s spacetime geometry. We expect that the gravitational wave observables will somehow “encode” the information about the spacetime structure. On the other hand, it has been known for some time that the geometry around an axisymmetric body can be described by its (Geroch-Hansen) multipole moments. Therefore one can speculate that using the multipole moments can prove to be a helpful tool for extracting this information. We will try to demonstrate this in this talk, following the procedure described by [F. D. Ryan, Phys. Rev. D 52 5707 (1995)] and [T. P. Sotiriou and T. A. Apostolatos, Phys. Rev. D 71 044005 (2005)].

#### 24. [astro-ph/0610920]

*Gravitational wave stochastic background from cosmic (super)strings*

Xavier Siemens, Vuk Mandic, Jolien Creighton  
30 Oct 2006

**Abstract:** We consider the stochastic background of gravitational waves produced by a network of cosmic strings and assess their accessibility to current and planned gravitational wave detectors, as well as to the big bang nucleosynthesis (BBN), cosmic microwave background (CMB), and pulsar timing constraints. We find that current data from interferometric gravitational wave detectors, such as LIGO, are sensitive to areas of parameter space of cosmic string models complementary to those accessible to pulsar, BBN, and CMB bounds. Future more sensitive LIGO runs and interferometers such as Advanced LIGO and LISA will be able to explore substantial parts of the parameter space.

## LISA science source “coolness” survey

The design of LISA is not yet set in stone, and finalizing the design will involve further trades to maximize the scientific return of the mission within other constraints. An effort is underway to quantify scientific return as a function of certain key design features and available cost information, to support assessment of an optimal LISA mission.

The scientific value of LISA comes from its ability to observe various classes of gravitational-wave sources. Two factors contribute to this value: the *likelihood of detection* of a particular source, and the *intrinsic scientific interest* (“coolness”) of that source. The likelihood of detection is an estimate we make by combining a given mission design with our best astrophysical models. But the “coolness” of the different sources can only be assessed by polling the scientific community. That is you, and this is your chance!

You are hereby given a total of 30 coolness points to allocate among the following six classes, each class representing a particular type of observation that might come out of the LISA mission. Distribute your 30

points according to the relative degree of interest you would have in such an observation. You may assign zero points to some, or even put all your points in a single source. The six classes are:

[ ] *Detection* of an isolated high-frequency (> 2mHz) Galactic white-dwarf binary.

[ ] *Resolution* of a low-frequency (< 2mHz) Galactic white-dwarf binary from the confusion background of such sources.

[ ] *Detection* of a supermassive black-hole (SMBH) binary merger.

[ ] *Observation* of such a SMBH binary system at least 6 months prior to merger (long enough to estimate sky position and distance).

[ ] *Detection* of an extreme-mass-ratio inspiral.

[ ] *Detection* of a primordial stochastic background.

Please post your ranking in the LISC discussion board at <http://www.lisa-science.org/liscforum/1-general/1>, with your name and some information about your research interests and activities, and any other valuable comments you would like to give. The LISA Project will consider your preferences in its prioritization of LISA mission designs.

We would like to have your inputs by the end of November 2006, if possible. This will permit us to summarize results at the upcoming meeting of the LISA International Science Team in mid-December, and to report the survey results in the next issue of *The LISA Newsletter*.

# What's new on the LISA Programmatic Front?

The US National Research Council is undertaking a major review of the NASA Beyond Einstein Program that began this Fall and will likely extend until June 2007, with a report release date in September of 2007. While reviews are always very time-intensive, the LISA community welcomes this chance to showcase the exciting science of LISA and to discuss the tremendous progress made in recent years in both the science and the mission implementation.

The committee web site can be found at: <http://www7.nationalacademies.org/ssb/BeyondEinsteinPublic.html>. The charge of the committee (named the Beyond Einstein Program Assessment Committee, BEPAC), includes the following tasks:

1. Assess the five proposed Beyond Einstein missions (Constellation-X, Laser Interferometer Space Antenna, Joint Dark Energy Mission, Inflation Probe, and Black Hole Finder probe) and recommend which of these five should be developed and launched first, using a funding wedge that is expected to begin in FY 2009. The criteria for these assessments include:

- Potential scientific impact within the context of other existing and planned space-based and ground-based missions; and
- Realism of preliminary technology and management plans, and cost estimates.

2. Assess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions. This second task element will assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the Decadal Survey.

The first meeting of the NRC BEPAC committee was held in Washington, DC on 06—08 November. Presentations were heard from each of the missions in the Beyond Einstein program as well as from speakers invited to summarize the science of the Beyond Einstein program. Scott Hughes was invited to speak on “Did Einstein have the Last Word on Gravity?” Craig Hogan and Karsten Danzmann represented the LISA mission, with Craig speaking about the science of LISA and Karsten providing an overview of the mission, measurement approach, and technology. It is fair to say that everyone thought that Craig, Karsten, and Scott gave excellent talks, certainly among the very best given by any of the speakers during the meeting. You can find all the presentations (minus the very nice movies of black hole mergers) at the committee web site indicated above.

The next meeting of the NRC BEPAC committee is expected to take place 30 January to 01 February 2007 in Irvine, California. Several additional meetings of the committee are anticipated in 2007, as well as “Town Hall” meetings to solicit community input. The project and the broader LISA science community have been working hard to prepare for these meetings, including developing several documents on science, mission architecture, data analysis, project management, and technology. They have also been responding to a set of questions submitted after the first meeting by committee members. These questions range from: “What are the ranges of rate estimates for different source categories with uncertainties?” to “What elements of the mission are unlikely to reach TRL (technology readiness level) by the early FY2009?” and “What is the plan for involving guest observers?” Altogether LISA has been asked to respond to twenty different questions.

Obviously, the NRC review will be a very important review for LISA. We encourage all members of the LISA community to talk to their colleagues about how exciting and revolutionary LISA is as a science mission and how important it is that LISA be selected to go forward towards implementation both in Europe and the US.

## The members of the Beyond Einstein Program Assessment Committee include:

**Charles F. Kennel**, co-chair  
Scripps Institution of Oceanography

**Joseph H. Rothenberg**, co-chair  
Universal Space Network

**Eric G. Adelberger**  
University of Washington

**Bill Adkins**  
Adkins Strategies, LLC

**James S. Barrowman**  
Independent Consultant

**David A. Bearden**  
The Aerospace Corporation

**Thomas Appelquist**  
Yale University

**Mark Devlin**  
University of Pennsylvania

**Joseph Fuller, Jr.**  
Futron Corporation

**Karl Gebhardt**  
University of Texas

**William C. Gibson**  
Southwest Research Institute

**Fiona A. Harrison**  
California Institute of Technology

**Andrew Lankford**  
University of California, Irvine

**Dennis McCarthy**  
Swales Aerospace Institute, ret.

**Stephan S. Meyer**  
The University of Chicago

**Joel R. Primack**  
University of California

**Lisa J. Randall**  
Harvard University

**Craig L. Sarazin**  
University of Virginia

**James S. Ulvestad**  
National Radio Astronomy Observatory

**Clifford M. Will**  
Washington University

**Michael S. Witherell**  
University of California, Santa Barbara

**Edward L. Wright**  
University of California Los Angeles

# LISC web portal update

The *LISA Newsletter* is distributed electronically and available in hard copy to all members of the LISA International Science Community (LISC), an informal network of researchers, maintained by the LISA International Science Team for the purpose of exchanging information about LISA with the wider science community.

Visit the LISC portal at [www.lisascience.org](http://www.lisascience.org) for LISA news, introductory and advocacy resources, useful links, and discussion boards among LISC members.



## Recent & upcoming LISA meetings

13-17 November 2006 Paris, France  
**Gravitational Wave Data Analysis**  
<http://luth2.obspm.fr/IHP06/>

November 26-December 1 2006 Playa del Carmen, Mexico  
**VII Mexican School on Gravitation and Mathematical Physics**  
<http://www.smf.mx/~dgfm-smf/EscuelaVII/index.html>

November 27-December 1 2006 Niigata, Japan  
**16th Workshop on General Relativity and Gravitation (JGRG16)**  
<http://jgrg16.sc.niigata-u.ac.jp/>

11-15 December 2006 Melbourne, Australia  
**23rd Texas Symposium on Relativistic Astrophysics**  
<http://www.texas06.com/index.php>

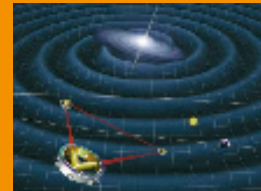
18-21 December 2006 Golm, Germany  
**11th Gravitational Wave Data Analysis Workshop (GWDaw-11)**  
<http://gwdaw11.aei.mpg.de/index.html>

5-10 January 2007 Seattle, WA  
**2007 AAS/AAPT Joint Meeting**  
<http://www.aas.org/meetings/>

22-24 January 2007 Tucson, Arizona  
**Rethinking Gravity: From the Planck scale to the size of the Universe**  
<http://www.physics.arizona.edu/gravity/>

8-13/14 July 2007 Sydney, Australia  
**GR18/7th Amaldi meeting**  
<http://www.amaldi7.com/>

For more LISA information:  
[lisa.nasa.gov](http://lisa.nasa.gov)  
[sci.esa.int/home/lisa](http://sci.esa.int/home/lisa)  
For technical and scientific details:  
[www.srl.caltech.edu/lisa](http://www.srl.caltech.edu/lisa)



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the LISA newsletter

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