# LISA Letter of Intent: Data analysis activities in The Netherlands

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**Abstract**

LISA is a joint ESA/NASA mission to detect and observe graviational waves by using interferometry between free-falling proof masses. This letter of intent (LoI) is in response to the ESA call for letters of intent from May 11, 2005 regarding a study of the data analysis requirements for LISA. It describes the interest in the Dutch community in participating in this data analysis study in support of the ongoing Mission Formulation phase for LISA. The present LoI outlines the proposed activities, the resources that can be committed to these activities, and the expected sources of funding.

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## Contents

# 1 Introduction

Gravitational waves are space-time distortions caused by celestial bodies that are accelerated or disturbed. The waves propagate through space-time, distorting other bodies in their path as well as the space between them. The resulting motions and distortions have extremely small amplitudes but can in principle be detected with laser interferometry and resonant detectors. Although a number of ground-based experiments are operational, future international plans are focused on the space-based laser interferometer LISA.

The scientific impact of gravitational wave detection and observation will be enormous. It will teach us about the physics of supernovae, neutron stars and black holes, thereby opening a new window on subatomic physics as well. It will also be a great step forward in cosmology, as gravitational radiation can provide information on the earliest stages of the universe (inflation). Moreover, LISA's data will provide for quantitative tests of general relativity.

Here, we describe the interest in the Dutch community in participating in the ESA planned data analysis study[1] in support of the ongoing Mission Formulation phase for LISA. In this context it is important to note that there are several existing graviational wave and related astroparticle physics research projects in the Netherlands.

- Within SRON, the Netherlands institute for space research, control and readout electronics for inertial sensors are being developed for the 'Inertial Sensor Test Module' (ISTM) project of the LISA Pathfinder mission. SRON is also contributing to detailed software models of the Inertial Sensor, which are included in the industrial 'End-to-End Simulator' being developed at EADS Astrium (Germany).

- Many of the questions addressed by the theoretical astroparticle physics community in the Netherlands are closely linked to the LISA science program. The investigations encompass physics beyond the Standard Model focusing on several mechanisms that may affect leptogenesis and baryogenesis, investigations in cosmic accelerators, string theory, cosmology and gravitation, as well as astroparticle physics research, such as the topology of cosmic defects, presence of extra dimensions and the understanding of inflation.

  Dutch research on astrophysical sources of gravitational waves takes place in Amsterdam, Leiden, Nijmegen and Utrecht (compact binary systems involving neutron stars, white dwarfs and/or stellar mass black holes, as well as super-massive black holes in galactic nuclei). Appendix A gives a brief overview of the Dutch activities in this field.

- The Netherlands is involved in the construction and use of the resonant gravitational wave detector MiniGRAIL at the University of Leiden. MiniGRAIL is a 68 cm diameter spherical antenna with a resonant frequency of about 3 kHz cooled to ultra-low temperatures. The first of its kind (developed in collaboration with Twente University), MiniGRAIL operates in conjunction with two cylindrical bar detectors, run by the INFN in Italy, thus providing coincidence measurements. Its primary target is the observation of gravitational radiation from non-axisymmetric instabilities in rotating single and binary neutron stars, and the radiation from mergers of small black holes or neutron stars.

In the following we describe the activities we envisage as part of the LISA data analysis study, the resources that can be committed to these activities, and the expected sources of funding.

# 2 Proposed activities

Here, we present areas of data analysis, astrophysics and physics that will be carried out by the Dutch LISA data analysis collaboration. The group at the Vrije Universiteit will set up a LISA data model that includes stochastic gravitational radiation. Subsequently, template searches will be executed on a data grid infrastructure. Scientists from NIKHEF in a joint effort with the research of relevant university groups will study the gravitational wave signals from inflation and phase transitions in various models and scenarios. The astronomy group at Nijmegen will study galactic sources, indirect detection of gravitational waves and complementary electromagnetic observations. Synergy between the LISA and XEUS missions will be explored by scientists at SRON.

## 2.1 Stochastic gravitational radiation and LISA data model

There is certain to be a stochastic background of gravitational radiation from numerous sources in various epochs during the evolution of the universe. These signals will be superimposed on each other in an incoherent way, with noise-like characteristics. It is important to understand and quantify the shape and intensity of this stochastic background both as a scientific problem in itself, as well as to distinguish possible signals from individual sources on top of this background.

A LISA data model (van den Brand, Ketel, 1 PhD) will be developed in close contact with the appointed ESA data analysis supervisor; it will build upon the detailed population model of galactic compact binaries constructed for the purpose of gravitational wave analysis by dr. G. Nelemans from the RU Nijmegen. The data model and accompanying analysis system software will be based on our experience with other projects (mainly large-scale particle physics experiments such as NMC, SMC, Hermes and LHCb) employing object-oriented technology. In this respect it is relevant to note, that NIKHEF is to become a TIER-1 center in the LHC data grid. The TIER-1 facility in Amsterdam was primarily designed for processing particle-physics data produced by the LHC experiments at CERN, but now other applications are being considered as well. NIKHEF has sufficient resources (both physical nodes and IT manpower) to run LISA template searches on its grid environment. The latter may be of particular interest for LISA for the planned EMRI searches. Various templates and analysis algorithms will be developed and assessed in their effectiveness to isolate signals from inflation and phase transitions (see also section 2.2).

Based on the above described software and grid infrastructure we will study activities during the formulation phase. This involves operation requirements, data acquisition constraints and limitations due to degraded mission performance and architectural problems. Again the precise activities will be defined in discussion with the ESA appointed data analysis supervisor.

## 2.2 Signals from inflation and phase transitions

The weakness of gravitational interactions implies that gravitational waves can propagate virtually unperturbed through the entire visible universe. This makes it possible in principle to probe the development of the very early universe with gravitational waves way beyond the time-scales probed by the WMAP (and PLANCK) space mission. In fact, the detection of primordial gravitational waves could become the most fundamental discovery to be made by LISA. If so, the discovery potential of the mission will be comparable to that of the cosmic microwave background (CMB) in recent years.

There are various candidate sources for primordial gravitational waves; we mention a few:

- Inflation. A period of rapid expansion of the early universe explains very well some of its global properties, such as its smoothness and flatness, as well as the spectrum of primordial density fluctutations. The physical mechanism at the root of such an inflation period is highly uncertain. By observing the fluctuations in space-time geometry caused by inflation, we learn more about the actual mechanism. Both LISA and PLANCK have the potential for providing such data, and thus cause a break-through in the field: LISA can search for the gravitational waves directly, whereas PLANCK (by its excellent angular resolution and capability to measure the polarization of the CMB) can determine the space-time fluctuations encoded in the CMB itself. With two independent ways of measurement, the interpretation of the data from each experiment can be checked and strongly improved.

- Phase transitions. It is possible that during the expansion and cooling of the early universe it experienced one or more phase transitions, *e.g.* an electroweak, a QCD or a GUT (gauge unification) transition. The resulting change in the structure of the vacuum, being a dynamical process, will leave its mark on the space-time geometry in the form of a spectrum of gravitational waves.

- Topological defects. When large-scale domains of space-time with a homogeneous vacuum structure are formed, topological effects like the formation of strings or domain walls can be produced at the boundaries. Such topological defects could decay under emission of gravitational radiation.

- Pre-big-bang physics. In certain quantum gravity models like string theory, the standard big-bang is a transition dominated by quantum effects between two different regimes of essentially classical space-time geometry. In such a scenario it is possible that information about the pre-big-bang structure is transmitted in the gravitational wave spectrum from the early universe.

In the framework of the LISA program, NIKHEF (the joint institute for subatomic physics of FOM, the University of Amsterdam, the Radboud University in Nijmegen, Utrecht University, and the Vrije Universiteit Amsterdam) will study the gravitational wave signals from inflation and phase transitions in various models and scenarios. These studies will constitute a joint effort with the research of relevant university groups. A PhD student has already been allocated to this project.

## 2.3 Galactic sources, indirect detection and complementary electromagnetic observations

At the Radboud University Nijmegen, current research on gravitational waves is done in two complementary topics. Firstly, the coupling of gravitational waves to magnetized plasmas is studied (Kuijpers, Moortgat). It was shown that there can be coherent interaction over large length scales, allowing all three fundamental low-frequency plasma wave modes to be excited by the gravitational waves. Recently, the prospect of detecting electromagnetic signals emitted by the plasma waves in the low-frequency radio wave domain has been studied and the first results open the exciting possibility of indirect detection of gravitational waves with the currently developed LOFAR.

The second topic is the Galactic population of ultra-compact binaries. There are many ultra-compact Galactic binaries in the LISA band. These both provide many detectable sources, as well as an extra “noise” background at the lowest frequencies. A small number of known ultra-compact binaries will serve as verification sources for LISA. In Nijmegen, population synthesis studies are combined with observational efforts aimed at finding more verification sources and studying the known ones in detail (Groot, Nelemans, Roelofs, van den Besselaar). The expected number of individually detectable Galactic binaries is found to be of the order of 10,000. Our expertise has led us to be particularly interested in the electromagnetic (in particular optical, IR, UV and X-ray) signals of the detectable LISA sources, and the advantages that can be obtained in combining observational efforts in electromagnetic wave bands with LISA measurement, *e.g.* the reduction of parameters that have to be fitted to the LISA data by measuring accurate positions of sources in the sky.

In order to further expand the above two complementary research efforts, a comprehensive program to study the electromagnetic signals of gravitational wave sources has started. In particular the plasma interaction of lower-frequency sources (*e.g.* super-massive black hole mergers) and the detectability of Galactic gravitational wave sources in the optical, infra-red, UV and X-ray bands will be studied.

It is expected that at least one new PhD student will be dedicated to this project, as well as current involved people (1 PhD student, 1 PostDoc, 2 part time senior staff). This topic gives a natural connection to the theoretical and observational efforts at the Universities of Utrecht and Amsterdam, related to the study of compact objects and extreme gravity.

The expertise and plans in Nijmegen will be valuable in the development of a serious LISA data model, as input on expected sources can be given, and conversely, the data analysis results will be used to determine which astrophysical questions regarding the formation and evolution of ultra-compact binaries, compact objects and gamma-ray bursts and what fundamental physics can be studied with LISA and what complementary electromagnetic observations are needed and feasible.

## 2.4 Synergy between LISA and XEUS

The recent discovery of the potentially brightest source of gravitational radiation in the sky, RX J 0816.3+1527, as an ultra compact binary X-ray source with a period of 5 minutes, shows the intimate relation between X-ray observatories and LISA. Detailed knowledge of the period and period derivatives of such sources will be a main input for LISA, both for directly detectable sources and to reduce the background at longer periods. XEUS, a mission considered for launch early in the period 2015-2025 in the ESA Cosmic Vision science programme, will be the next generation X-ray observatory. SRON plans for a major contribution to this mission, as follow-up to its present involvements as Principle Investigator Institute in the major X-ray observatories XMM-Newton and Chandra. X-rays provide a window on highly energetic plasmas and are as such a unique probe of the physics of Black Holes and Neutron Stars. For Extreme Mass-Ratio Inspirals (EMRI, a small compact object falling into a SMBH) detected with LISA, XEUS could provide confirming and additional information including X-rays from an accretion disk in the EMRI and the determination of the spin for SMBHs. On the latter, XEUS may do better than LISA, if SMBHs have higher spins. For the coalescence of SMBHs X-ray properties will provide information about the mass accretion including the physical properties during the merger. Furthermore, XEUS could provide a more accurate position when LISA detects a merger event, including the possible delay of the turn-on of the X-rays, and *e.g.* also redshifts for cosmological studies. The equation of state of hadronic and quark matter in Neutron Stars is being studied with high resolution X-ray spectroscopy. This allows the determination of limits on the mass-radius relation. The physical state of the matter in Neutron Stars has a distinct effect on its detectability with gravitational wave antennas. High-resolution X-ray spectroscopy is one of the main research topics of the Netherlands Institute for Space Research. Therefore contributions by SRON staff to the preparations for interpretation of data from the LISA mission, will especially address the synergy between the LISA and XEUS science.

Observations of the 0.511 MeV line with the gamma ray satellite INTEGRAL have lead to the suggestion that gamma rays originating from the centre of the galaxy are possibly the result of the decay of light dark matter particles. Moreover, gamma-ray observations of the Crab nebula, its high-energy synchrotron radiation, have prodded some groups to infer constraints on quantum gravity (i.e. upper limits on deviations from the equivalence principle.) Such issues will be addressed by the XEUS mission.

# 3 Logistics - Allocated resources and funding

Table 1 below describes the proposed involvement of tenured senior scientists and junior scientists in the LISA data analysis study. Note that funding has been already secured for this manpower[1].

**Table 1.** *Proposed involvement of tenured senior scientists and junior scientists in the LISA data analysis study. The names of the contact person for each group are listed in the 2$^{nd}$ column. The 3$^{rd}$ and 4$^{th}$ columns lists the type of position and the commitment in full-time equivalent (FTE) of research time.*

| Research group | Name | Position | FTE |
|---|---|---|---|
| NIKHEF | H van der Graaf | senior scientist | 0.1 |
| | JW van Holten | senior scientist | 0.2 |
| | G Koekoek | PhD | 1.0 |
| | F Linde | senior scientist | 0.1 |
| RU | P Groot | senior scientist | 0.1 |
| | J Kuijpers | senior scientist | 0.1 |
| | J Moortgat | PhD | 1.0 (until end 2005) |
| | G Nelemans | postdoc | 0.5 |
| | planned | PhD | 1.0 |
| SRON | W Hermsen | senior scientist | 0.1 |
| | P Jonker | senior scientist | 0.2 |
| | M Méndez | senior scientist | 0.2 |
| VU-physics | JFJ van den Brand | senior scientist | 0.5 |
| | T Ketel | senior scientist | 0.5 |
| | planned | PhD | 1.0 |

Additional funding may become available because in 2004 a number of leading researchers in the Netherlands, originating from astronomy, physics and space research, have started to investigate the opportunities for a well-structured research program in the field of astroparticle physics. As a result of this effort a strategic plan[2] has been submitted recently to NWO (Dutch science organization). If approved, additional funding will become available for participating groups.

[1] SRON staff concentrates on X-ray properties of related sources. Note that the financing of the RU PhD student is at this moment not certain.

The strategic plan is centered on three major research initiatives that were chosen because of their scientific potential and the availability of unique Dutch expertise in each of these domains: a) radio detection of cosmic rays; b) deep-sea neutrino detection; c) gravitational wave detection. Moreover, by building upon important previous Dutch investments (LOFAR , ANTARES and MiniGRAIL) in these research areas, the environment is created for a full exploitation of these instruments, which - at the same time - forms the starting point for a prominent participation in three large international research collaborations (the Pierre Auger Observatory, KM3NeT and LISA). A strong theoretical research effort and an equally important outreach program will supplement the chosen research topics. Taken together the choices made should result in a strong and internationally visible research program on astroparticle physics research in the Netherlands, thereby ensuring an active role of the Netherlands at this new frontier of science.

The proposed interdisciplinary research program in astroparticle physics will run from 2006 to 2015 with a total estimated budget of about 70 MEuro, of which 40 MEuro will be provided by the participating universities and research institutes (NIKHEF, SRON, KVI, and ASTRON). Hence, additional resources - increasing from 1.5 MEuro in 2006 to 3.2 MEuro in 2008 and later years - are needed to realize this challenging research program. We expect that on average about 0.5 MEuro/year will be allocated to gravitational wave research.

# A Appendix: Theoretical astroparticle physics research in the Netherlands

**Table A.1.** *Present involvement of tenured senior scientist in theoretical astroparticle physics research in the Netherlands. The names of the scientists involved are listed in the 2nd column. The 3rd column lists the primary interest of each group.*

| Research group | Staff | Theoretical astroparticle physics subjects |
|---|---|---|
| UvA-astronomy | Wijers | GRBs and their environment, implications for stellar evolution and cosmology |
| UvA-physics | Smit, de Boer, | Nonequilibrium and finite-temperature field theory, phase transitions in cosmology, baryogenesis, string theory & cosmology |
| VU-physics | Mulders, Boer | QCD phase transitions in the early universe and in neutron and quark stars |
| NIKHEF-theory | Van Holten, Schellekens | Cosmology, inflation, gravitational waves, quantum gravity, string theory, detection of UHE cosmic rays |
| RuG-astronomy | Van de Weijgaert | theory and simulations of the formation of large scale structures in the universe |
| RuG-physics | Bergshoeff, de Roo, Pallante | CP violation in hadrons on the lattice, string theory and cosmology, extra dimensions |
| LU-physics | Achucarro | the early universe, topological effects |
| RU-astronomy | Kuijpers, Falcke Groot | Coherent radio emission from cosmics rays; jets from AGNs; detection high-energy cosmic rays; gravitational waves |
| UU-astronomy | Achterberg, | ultra-high energy cosmic rays, extreme relativistic plasmas |
| UU-physics | Loll, Prokopec, 't Hooft | baryogenesis, inflation, quantum cosmology alternative theories of gravitation and cosmology, dark energy |

Part of the theoretical projects mentioned above is supported by the NIKHEF theory program and the FOM research programs 'Fundamental Interactions' and 'String Theory and Gravity'. Together they form the Network for Theoretical High Energy Physics.

# References

[1] Call for Letters of Intent (`http://lisa.esa.int`), ESA, 23 May 2005.

[2] Strategic Plan for Astroparticle Physics in the Netherlands (see `http://www.astroparticlephysics.nl`); April 2005.