LARS

Large Space Interferometer for Cosmology

Proposal to the European Space Agency
for a Flexi Mission
in Fundamental Physics

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Excecutive Summary

The currently proposed space based interferometric gravitational wave antenna LISA [1] reaches its optimal sensitivity in a frequency range of about 10^{-1} to 10^{-3}Hz. In this range one expects to find a variety of astrophysical sources [2] such as massive black holes, neutron stars and binary systems. In order to observe supermassive black holes (SMBH's) $> 10^{7} M_{\odot}$, primordial gravitational wave background and other sources of cosmological interest, we aim at pushing the range of observable frequencies down to 10^{-5}Hz. We propose a large interferometric gravitational wave detector in space as a tool for cosmology. Main emphasis is put on a frequency range of about 10^{-3} to 10^{-5}Hz where we expect to observe the primordial background of gravitational waves and supermassive black holes. Sufficient sensitivity in this frequency band is obtained by choosing the arm length of the interferometer to be of the order of 1 AU. The main problem we have to face are distortions due to thermal effects. LARS comprises three spacecraft in a heliocentric orbit at 1 AU displaced by 120 degrees along the orbit of the earth at the corners of an equilateral triangle. Together they form a Michelson interferometer with an arm-length of $\sqrt{3}$ AU. Each spacecraft contains lasers and free-flying test masses.

1 Introduction

The currently proposed space based interferometric gravitational wave antenna LISA [1] reaches its optimal sensitivity in a frequency range of about 10^{-1} to 10^{-3}Hz. In this range one expects to find a variety of astrophysical sources [2] such as massive black holes, neutron stars and binary systems. In order to observe supermassive black holes (SMBH's) $> 10^7 M_\odot$, primordial gravitational wave background and other sources of cosmological interest, we aim at pushing the range of observable frequencies down to 10^{-5}Hz. This is mainly achieved by increasing the arm length of the interferometer by two orders of magnitude as compared to LISA, i.e. to the order of 1 astronomical unit. The main problems we have to overcome here are finding a suitable orbit and controlling the noise due to thermal fluctuations of the sun. The latter must be regarded as the most important source of noise in this frequency range.

Present models of inflation and phase transitions in the early universe, which are related to spontaneous symmetry breaking of gauge theories, e.g. at the energy scale of grand unification, predict different spectra of primordial gravitational waves [3]. Resolving the spectra would provide us with information about much earlier cosmological events than can be seen by electromagnetic astronomy. Furthermore the fundamental interactions can be probed at energies that are far beyond the reach of earth based particle accelerators.

A second important source of gravitational waves, whose study would contribute to our understanding of cosmology and formation of galaxies, are phenomena involving SMBH's. These include mergers of SMBH's (e.g. caused by the collision of galaxies), the inspiral of medium sized and small black holes into SMBH's, which is interesting for the formation of galactic nuclei, and the inspiral of solar type stars into SMBH's, which should not be disrupted by tidal forces, if the SMBH has a mass of at least 10^9 solar masses [3].

2 Basic properties of LARS

The basic idea is to extend the design concept of LISA, i.e. a cluster of three spacecraft, that provide three Michelson interferometers, to the desired wave lengths. The project we propose is called LARS: Large Space Interferometer. In order to get low signal to noise at frequencies as low as 10^{-5}Hz it is necessary to increase the arm length by a significant factor to the order of one astronomical unit. Here we are limited by the diameter D of the reflecting mirror, the laser wavelength λ and the ratio of the received to the transmitted laser power. More precisely this tradeoff is described by the equation

$$P_{\mathrm{out}} = \frac{1}{2}\frac{D^4}{\lambda^2 L^2} P_{\mathrm{in}}, \tag{1}$$

where P_{out} and P_{in} denote the laser power at the transmitter and receiver respectively and L is the arm length of the interferometer, i.e. the distance between the spacecraft.

Plugging in reasonable numbers, i.e. $\lambda = 532$ nm, $P_{\text{out}}/P_{\text{in}} = 10^{-11}$, we see that we can even reach an arm length of 3 AU with a mirror of diameter one meter.

The next question to ask is, where to put such a big instrument? Several possibilities come to mind.

- A heliocentric orbit at approximately 5 AU, 180 degrees phase

  shifted with respect to Jupiter. The cluster of three spacecraft could be arranged in a LISA-type fashion. The major drawback comes from the huge amount of propulsion and time needed to get the spacecraft there.

- An arrangement of the cluster in the Lagrangian points L_2, L_4 and L_5 of the earth. This constellation shows the inconvenient properties of unequal arm lengths and a small distance to the earth.

- A cluster formed by three spacecraft in a heliocentric orbit at one AU, with relative angles of 120 degrees, phase shifted 20 degrees with respect to the earth. This corresponds to an arm length of $\sqrt{3}$ AU.

A detailed study was carried out only for the last possibility due to the fact that it combines long equally sized arms with relative ease of reaching the orbit. Mission analysis shows that within approximately 5 years the final orbit can be reached with a reasonable amount of fuel, thereby well fitting into the Ariane 5 payload capability.

Since our configuration of spacecraft is bound to stay in the ecliptic plane, reconstruction of the full information contained in a gravitational wave needs special consideration. In particular the angular resolution of an incoming signal needs to be discussed. In the case of LISA the changing orientation of the interferometer plane improves the angular resolution due to Doppler modulation of the signal [4]; LARS has a fixed center-of-gravity and therefore the Doppler modulation yields no information about the direction of the source. Nevertheless angular resolution is still possible for LARS, since the signals associated with each of the two different polarization modes of gravitational waves $(h_+, h_\times)$ show a characteristic pattern of modulation dependent on the position of the source (ϑ, φ) in the rotating rest-frame of LARS during the period of one year. Thus, in principle, the position of the gravitational wave source can be extracted from the signal modulation.

3 Noise Budget

Like with LISA the sensitivity of our detector is limited at high frequencies by the photon shot noise and the blow up of the geometrical factor [1]. However, we expect to have a reasonable signal to noise up to frequencies of about 10 mHz.

More detailed considerations are needed for the low end. Here the major source of noise comes from spurious accelerations of the proof mass due to thermal distortions, Newtonian gravity noise, electromagnetic forces, etc. The hardest task is to control the radiation pressure caused by the thermal fluctuations of the sun which becomes the dominant term at a frequency of about 10^{-4}Hz. We shall discuss this effect in some detail. The radiation pressure is approximately given by

$$\delta P \approx \frac{4}{c}\sigma T^3 \Delta T \left(\frac{\varepsilon_w(2-\varepsilon_{pm})}{\varepsilon_w + \varepsilon_{pm} - \varepsilon_w \varepsilon_{pm}} \right), \tag{2}$$

where σ denotes the Stefan-Boltzmann constant, T the absolute temperature, ΔT the temperature fluctuations and the factor at the right involves the emissivity of the proof mass and the wall respectively. The density fluctuations ΔQ of the sun are assumed to be about 1% of the total radiation power of 1440 W/m^2 and we use the equation

$$\frac{\Delta Q}{\Delta t} A = CM \frac{\Delta T}{\Delta t}, \tag{3}$$

where Δt denotes the typical time interval, A the surface area of the spacecraft, C the specific heat and M is the mass of the proof mass. The resulting temperature fluctuations ΔT hence can be computed to be of the order of $5 \cdot 10^{-3}$K. However, such big distortions are unacceptable and we have to look for some active temperature control strategies as passive ones won't do the trick. Therefore we propose to heat the spacecraft at an amount of several K above the fluctuation peeks. This has to be achieved by a feedback control system that keeps the temperature constant to an accuracy of 10^{-6}K. The amount of power needed was estimated to approximately 5 W/K, which seems quite manageable. The only drawback comes from the necessity of a high accuracy temperature measurement at frequencies of 10^{-4}Hz. Assuming that we can suppress ΔT down to 10^{-6}K at these frequencies (which goes beyond present technology) and also gaining one order of magnitude from improvement in the emissivity term we can suppress the radiation power distortions to

$$\delta P \approx 10^{-15} \mathrm{m\ s^{-2}}/\sqrt{\mathrm{Hz}}. \tag{4}$$

Accordingly we estimate the strain to be approximately 10^{-23} at 10^{-4}Hz and approximately 10^{-21} at 10^{-5}Hz respectively, which finally gives us the sensitivity curve of our instrument for a one year observation time as shown in Fig. 1.

4 Science operations and archiving

The overall responsibility for the mission rests with the ESA Directorate of the Scientific Programme. Mission control will be the responsibility of the Directorate of Operations. The routine operational phase will be supported by the ground stations in Villafranca and Perth from where the data will be routed to the Mission Control Centre (MCC). The operations conducted from the MCC include scheduling and planning of spacecraft operations, monitoring and control of status and proper functioning of the spacecraft, and excecution of flight control.

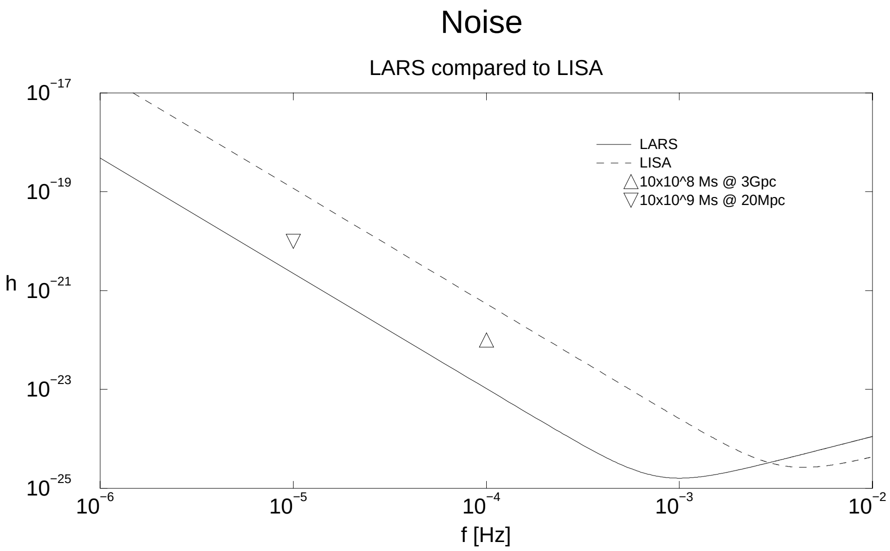

Figure 1: shows the noise curves of the LISA and LARS; the strain amplitude *h* corresponds to the *rms* detector noise for a one year observation. Additionally two possible sources are shown: △ estimates the signal from a $10M_\odot$ black hole spiraling into a $10^8M_\odot$ SMBH at 3 Gpc (redshift of $z = 1$), for ▽ the bigger black hole has $10^9M_\odot$ and the distance is 20 Mpc (roughly the distance to M87 in the Virgo cluster).

Upon receipt of the telemetry data in the MCC, the housekeeping packets will be analysed by the MCC in order to check the health of spacecraft and instruments. Payload housekeeping and science data will be forwarded from the MCC to the Science and Archiving Center (SAC) located at a PI institute to be selected through the AO, where the status of the payload will be monitored. Any desired manoeuvre commands will be sent to the MCC for uplinking. The SAC will calibrate the payload data and distribute them to the PIs.

According to the ESA policy on data rights, for the first six months after the end of the mission, the science team will have exclusive rights over their data. Thereafter, all science data (raw, calibrated, housekeeping) will have to be submitted by the investigators to the SAC, where the data will be stored and can be accessed by the wide scientific community.

The teams providing the various data sets will have the tasks to perform a thourough end-to-end analysis, to calibrate the science data, develop appropriate software for data analysis, produce an explanatory supplement, and to deliver these items in a timely fashion to the SAC.

The SAC will have the tasks to ensure the timely delivery of the above items, to verify the contents, to produce an appropriate number of copies of data and supplements, and to respond to requests from the user community and send out data and supplements as requested.

5 Management and funding

The proposed procurement scheme is based on the concept that the payload will be provided by Principal Investigators (PIs), with funding from ESA's Member States. Payload selection would take place via the normal procedure which includes issue of an Announcement of Opportunity (AO), technical and scientific evaluation of proposals, and approval by the SPC.

ESA would be responsible for spacecraft procurement and system testing, launch and operations. A Science Working Team comprising the PIs, the Experiment Manager, an ESA Project Scientist, and an ESA Project Manager would be established to direct the project. Nationally funded payload systems, such as lasers and telescopes, will be constructed at PI institutes. One institute would perform the overall management, integration, and testing of the payload under the responsibility of an Experiment Manager who would be the single-point interface to the ESA Project Team.

6 Communication and outreach

The theory of gravity is one of the most fundamental, yet least understood of all physical theories. Observations and experimental advances are constantly triggering new theoretical work in this field. After all, it was the (unjustified) claim of experimental detection of gravitational waves in the 1960s that spurred a vigorous theoretical debate about the reality of these effects, following 50 years of quiescence after the initial prediction by Albert Einstein.

The award of the 1993 Nobel Prize in physics for the discovery of the binary pulsar PSR 1913 and its use to provide indirect proof of the existence of gravitational waves has highlighted the field and has stimulated the interest of many people, scientists and amateurs alike.

Although gravitation and gravitational waves are among the least understood scientific disciplines, they appeal to the imagination of people of a wide range of experience and background. Gravity does not suffer from the same public understanding problem that other scientific fields have. On the contrary, almost everybody has an immediate intuitive understanding of gravitation as it pervades our lives permanently and in everyday experience. This results in many demands for talks in this field to be given to astronomical societies, physical societies, and particularly to the general public. There are also requests every year for contributions to radio and TV programmes on science. The concept of a curved space can be easily made plausible even to lay audiences by the use of suitable demonstrations.

Gravitation and the technology to measure it are easily imagined and appear to be an area of fascination to the population at large. Describing research in this area provides an opportunity to captivate the public imagination and contribute to the scientific education and to the widespread acceptance of science.

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