Journey to the edge of time: The GREAT mission.

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We are surrounded by radiation that originated from the big bang. It has traveled to us from the farthest reaches of the Universe, carrying with it an unaltered record of the beginning of time and space. The radiation is in the form of gravitational waves - propagating ripples in the curvature of spacetime. We describe a mission to detect these Gravitational Echos Across Time (GREAT) that would open up a new window on the very early universe. By studying the gravitational echoes of the big bang we will gain insight into the fundamental structure of matter, gravity, and how the Universe formed.

Submitted to NASA’s 2003 SEU Roadmap Team as a “Vision” mission. Vision missions typically require technologies that are not yet developed - this is certainly true of GREAT.

I. INTRODUCTION

The Universe today is filled with fossil relics of the big bang. Studies of one of these relics - the Cosmic Microwave Background (CMB) - have revolutionized our understanding of the early Universe. But microwaves and other forms of electromagnetic radiation are unable to penetrate the hot plasma that filled the Universe until 300,000 years after the big bang. To see beyond this recombination barrier we need to study another fossil relic of the big bang - the Cosmic Gravitational wave Background (CGB). These gravitational waves were produced when the Universe first formed, and their extremely weak coupling to matter allowed them to propagate freely through the dense plasma that filled the early Universe. In most models of the early Universe the CGB has a quantum mechanical origin, making its detection a probe of quantum gravity.

It is not easy to detect waves that can pass virtually unattenuated through the densest matter in the Universe, but the task is not impossible. A GREAT detector consisting of two independent gravitational wave interferometers that are enhanced versions of the LISA instrument (Laser Interferometer Space Antenna) would have the sensitivity required to detect the Cosmic Gravitational wave Background predicted by standard inflation models. Indeed, the main challenge is not building a detector with sufficient sensitivity, but rather, picking out the CGB from the multitude of astrophysical sources of gravitational waves. The final design of the GREAT mission will depend on lessons learned from the LISA mission. LISA will serve as a stepping stone in the development of the advanced optical and drag free systems required by GREAT, while at the same time providing crucial data about the astrophysical foregrounds that GREAT will have to contend with.

II. WHY GO TO SPACE?

The gravitational wave spectrum is broadly divided into high and low frequencies, with one Hertz as the dividing line. Seismic, atmospheric and other environmental disturbances limit ground based gravitational wave detectors to the high frequency portion of the spectrum above 10 Hertz. In contrast, space based detectors can operate at practically any frequency.

Standard inflation theories predict that the amplitude, $h$, of the relic gravitational waves increases at low frequencies such that $h \sim f^{-\alpha}$, where $f$ is the frequency and $\alpha \approx 1.5$. According to this prediction, the gravitational wave background in the frequency range accessible from space will have an amplitude thousands to trillions of times greater than in the frequency range accessible on Earth.

III. SCIENCE POTENTIAL

The CGB contains a wealth of information about the very early Universe. The amplitude and energy spectrum of the CGB provides a sensitive probe of the physical processes at work during the formation of the Universe. The gravitational waves produced during the big bang are expect to have a quantum origin, making the CGB a direct
experimental test of quantum gravity. The leading theory of the early universe, Inflation, predicts that gravitational waves will be produced as the result of parametric amplification of quantum fluctuations in the gravitational field. More speculative string theory models of the early universe give a range of predictions for the CGB spectrum that differ significantly from standard Inflation models. A direct measurement of the CGB power spectrum would help to pin down the correct theory of quantum cosmology.

To date, observations have told us very little about the CGB power spectrum. The existing experimental bounds are shown in Fig. 1, along with the regions of the spectrum that will be probed by various gravitational wave detectors. Also shown is the prediction from standard Inflation with a tensor-scalar ratio of 0.01. The spectrum is expressed in terms of $\Omega_{gw}(f)$ - the energy density of gravitational waves, in units of the critical density, per logarithmic frequency interval. Neither the ground based LIGO (Laser Interferometric Gravitational Observatory) detectors, nor the space based LISA detector, will have the sensitivity required to detect the spectrum predicted by Inflation. To do so will require the GREAT detectors described in the next section.

If we can achieve this sensitivity, then the GREAT mission has the potential to probe physics at the Planck scale, test the inflationary paradigm and to detect the creation of matter at the electroweak phase transition. Next, we highlight four of the potential important science questions probed by GREAT.

A. Inflationary models

The combination of a CMB polarization mission, such as CMBPOL, that measures gravity modes on the horizon size and the GREAT mission will enable us to probe the shape of the inflaton potential. Since the amplitude of the gravity wave signal depends on the Hubble parameter when the mode leaves the horizon, we will be able to directly probe inflationary physics. The lever arm provided by the two measurements will be very powerful. We will be probing the physics of inflation at two different scales and will be able to perhaps reconstruct the inflationary potential.

B. Probing the Planck Scale

String theorists suggest that Planck scale physics can produce a dramatic signature in the gravity wave background. Eather et al. argue that the breakdown of locality in string theory can produce significant deviations in the amplitude and shape of the gravity wave spectrum. Kaloper et al. show that even if string theory does not violate locality it will modify the Lagrangian by adding non-minimal coupling terms of order $p^2/M^2$ where $M$ is the string mass scale. They argue that string theories give rise to correction terms of order $10^{-1} - 10^{-7}$ rather than the $10^{-11}$ amplitude terms that arise in inflationary models. These terms alter the relationship between the tensor mode slope and the ratio between the amplitude of the tensor mode signal and the amplitude of the scalar mode signal. Since these correction terms are scale dependent, they will have different effects on gravity waves at the two different scales. This scale dependance appears in many versions of string cosmology.

C. TeV-PeV scale physics: the origin of matter and forces

After inflation, the universe begins to cool and slowly expand. GREAT is probing the physics of the universe when its temperature was in the GeV - PeV range. During this period, the universe underwent a series of phase transitions. These phase transitions, if they are violent enough, will produce a detectable signal in the gravity wave background. In standard physics models, the universe went through two important phase transitions in the GREAT frequency range: the QCD phase transition during which quarks where bound into protons and neutrons and the electroweak phase transition that transformed the basic forces into the form that we observe them today. While the gravity wave signal in minimal electroweak models is too small for detection ($h \sim 2 \times 10^{-27}$ at a characteristic frequency of $4 \times 10^{-3}$ Hz), gravity waves from more strongly first-order phase transitions, including the electroweak transition in nonminimal models, have better prospects for detection. Electroweak baryogenesis requires non-minimal models, so that a gravity wave background detection could be a direct signal of the origin of matter itself!

In brane world models, the largest compact dimension can produce an imprint on the gravity wave background. In these models, the fundamental scale of gravity is only 1 - 1000 TeV. When the universe cooled through this temperature, it can generate gravity waves in the detectable range of LISA and GREAT.
D. Black hole Mergers: Science from the Foreground

The greatest obstacle to detecting the CGB - the astrophysical foregrounds - can also be viewed as a major science goal for the GREAT observatory. A very low frequency mission would be able to detect every compact supermassive black hole binary in the Universe, while an intermediate frequency mission could detect every compact Neutron star binary in the Universe. The supermassive black hole binaries would provide insight into galactic evolution and merger, while the Neutron star binaries would provide insight into the endpoint of stellar evolution.

IV. MISSION DESIGN

The GREAT detectors could potentially operate anywhere in the range $10^{-7} \rightarrow 10$ Hz. Going below $10^{-7}$ Hz is not practical as observing a single cycle would take over a year, while frequencies above 10 Hz are best handled by ground based detectors. The basic design of the detectors would be the same as for LISA: laser interferometers monitoring the separation of three or more free-floating proof masses that are shielded from non-gravitational disturbances by the surrounding spacecraft. The GREAT mission will likely differ from LISA in the number of interferometers, orbital configuration, baseline, laser power, optics, and drag-free performance. The technologies required are well beyond what are currently available, but there is no fundamental reason why the performance levels can not be reached.

The final design will depend on the frequency window that is chosen, and the choice of frequency window will depend on what we learn about astrophysical foregrounds in the next decade. Based on our current understanding of the foregrounds, there appear to be two distinct choices for the GREAT observatory\[15\]. The first is a very low frequency option\[14\], operating in the range $10^{-7} \rightarrow 10^{-5}$ Hz, that exploits the expected increase in the amplitude of the CGB at low frequencies, and a tailing off in the amplitude of astrophysical sources below $10^{-5}$ Hz. The second is an intermediate frequency option, operating in the range $10^{-2} \rightarrow 1$ Hz, that exploits the transient nature of the astrophysical foregrounds at frequencies above $10^{-2}$ Hz. Each option has its own set of pros and cons, and its own set of technical challenges. In either case, it is important that the noise level in the observatory is well below the CGB signal so that astrophysical foregrounds can be removed.

A. Very Low Frequency Mission

The key technology for low frequency operation is the drag-free system that shields the proof mass from non-gravitational disturbances. At the heart of the drag-free system are the acceleration detectors. For a very low frequency mission to be viable, accelerometer performance would need to improve by several orders of magnitude beyond that envisioned for the LISA mission. It is unlikely that accelerometer improvements alone will be enough to bridge the gap between LISA’s low frequency performance and the requirements of the GREAT observatory. The baseline of the interferometer will also have to be increased, which will necessitate a change in the type of orbit used. The LISA design employs a cartwheeling orbit with a five million kilometer baseline. Changing to circular orbits with the spacecraft arrayed about the Sun leads to a factor of 50 increase in the baseline while maintaining a one AU orbital radius. The main drawback of this orbital configuration is a lack of directional sensitivity compared to the LISA orbits. It may be necessary to increase the baseline further by increasing the orbital radius to Martian or even Neptunian scale. This has the added advantage of reducing thermal noise in the spacecraft, but at the cost of solar power to run the spacecraft. Contrary to ones natural intuition, the larger baseline missions do not require larger telescopes or more powerful lasers than the LISA mission.

To give a concrete example, a very low frequency GREAT observatory with a $2.6 \times 10^8$ km baseline and accelerometers sensitive to accelerations of $10^{-18}$ m s$^{-2}$ Hz$^{-1/2}$ would be able to detect a gravitational wave background generated during the inflationary epoch at frequencies between $10^{-6}$ and $10^{-5}$ Hz (Fig. 2).

Once the desired sensitivity has been reached, a method has to be found to distinguish between instrument noise and the CGB, as both produce a stochastic signal in the detector. One method is to simultaneously operate the observatory in what are know as Sagnac and Micheleon modes. The Sagnac mode is fairly insensitive to low frequency gravitational waves, making it a useful tool for monitoring the noise in the more sensitive Michelson mode\[17\]. The advantage of this system is that it can be implemented using a single interferometer. The other alternative is to fly two independent interferometers and cross-correlate their output\[18\]. The gravitational wave signal will be common to both interferometers, while the detector noise will be independent. Consequently, the signal to noise ratio grows as the square-root of the number of cycles observed. The drawback of operating at low frequencies is that few complete cycles can be observed in one year, making the cross correlation of two interferometers inefficient.
B. Intermediate Frequency Mission

An intermediate frequency mission would require significant improvements in laser, optical and drag-free technology. To accurately track the movements of the proof masses requires a large number of photons. The more photons the better the measurement. The position sensing improves as the square of the size of the telescopes used to transmit and receive the laser signals, and as the square root of the laser power. Larger telescopes also reduce the error caused by laser pointing instability. The baseline of an intermediate frequency mission has to be shorter than the LISA mission to avoid losing sensitivity to waves whose wavelength fits inside the interferometer.

As a concrete example, a GREAT observatory comprising two independent interferometers, each with $5 \times 10^5$ Km baselines, 100 W lasers, 8 m telescopes, and accelerometers capable of detecting $10^{-17}$ m s$^{-2}$ Hz$^{-1/2}$, would have the sensitivity required to detect gravitational waves produced during an inflationary epoch of the early universe (Fig. 3).

The increased laser power and large optics require a different spacecraft design from the LISA mission. The telescope design could be based on Next Generation Space Telescope (NGST) technology. To have two independent interferometers, a total of 8 spacecraft are required. They are arranged in a square with two spacecraft at each corner. The spacecraft would have one large telescope for sending and receiving signals along the interferometer arms, and a second smaller telescope for exchanging phase information between the corner pair (Fig. 4).

A more radical design option for an intermediate frequency mission would be to shorten the baseline further and use active position control to operate the detector as a power-recycled Fabry-Perot interferometer, as is done at the Earth based observatories.

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FIG. 1: Observational bounds on the CGB power spectrum, $\Omega_{gw}(f)$, are indicated by the solid light blue boxes. The bounds are derived from the CMB anisotropy, Pulsar timing and Big Bang Nucleosynthesis. The region of the spectrum that will be probed by cross-correlating the first generation of LIGO detectors is indicated in black. The regions of the spectrum that would be probed by LISA and the GREAT observatories are indicated in green and red respectively. The blue curve is the spectrum predicted by Inflation with a tensor-scale ratio of 0.01.

FIG. 2: The solid lines are sensitivity curves for two variants of a VLF mission. The one to the right is described in the text, while the one on the left orbits at 10 AU. The dotted line indicates the amplitude of the CGB in an inflationary model with $\Omega_{gw} = 10^{-16}$. The frequency, $f$, is measured in Hz, and the strain spectral density $\tilde{h}$ is measured in Hz$^{-1/2}$. 
FIG. 3: The solid line shows the sensitivity that can be achieved by cross-correlating the intermediate frequency interferometers described in the text. The correlation is performed for one year with a frequency resolution of $\log(f) = 0.1$. The frequency, $f$ is measured in Hz, and the strain spectral density $\tilde{h}$ is measured in $\text{Hz}^{-1/2}$.

FIG. 4: The relative orbital configuration that gives two independent interferometers.