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A STUDY OF THERMAL NOISE

by

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Submitted to the Department of Physics in August, 1994
in partial fulfillment of the requirements for
the degree of Doctor of Philosophy in Physics

Abstract

Thermal noise will be a fundamental limit to the sensitivity of the Laser Interferometer Gravitational Wave Observatory (LIGO) in the frequency band where astrophysical sources should be detected. A study of thermal noise in mechanical systems helps to predict the noise floor of high sensitivity experiments such as LIGO and also gives insight to the loss mechanisms in macroscopic systems. This thesis investigates the thermal noise in wires that support the test masses of a gravity wave detector and in the internal normal modes of the test masses themselves.

The thermal noise of a pendulum is calculated by considering the losses in the flexure of the thin fibres that support the pendulum mass. An experimental investigation of thermoelastic damping was done by measuring the Q's of thin fibres made of tungsten, sapphire, silicon and fused quartz. Tungsten had the highest losses with Q's on the order of 10^3. Fused quartz had the lowest losses with Q's between $10^5 - 10^6$. The results indicate that thermoelastic damping is at best only an upper limit for the Q of a wire.

The internal thermal noise of the gravity wave detector test masses depends upon the frequency dependence of the loss mechanism in the test mass material (in this case, fused quartz-SiO_2). The design and noise sources of a high sensitivity special purpose interferometer to measure the thermally excited motions in a thin disk of fused quartz are presented. The RMS thermally driven motion of the mechanical resonances from normal modes between 8 kHz and 20 kHz was $4 \times 10^{-13} cm$ and the typical Q between 5×10^3 and 10^5. The measured mechanical noise of the system was $2 \times 10^{-15} cm/\sqrt{Hz}$ between 1 kHz and 20 kHz which was too large to be attributed to the off-resonance thermal noise from one of the measured mechanical modes of the plate. Various candidates for this noise are presented. Future experiments that would lead to a better understanding of the measured noise are discussed.

A possible microscopic model for the loss mechanisms in fused quartz is presented.

Finally, a method to monitor the internal thermal noise directly in future advanced gravity wave detectors is discussed. The optical experiment performed in this thesis is a prototype for such a technique.

Thesis Supervisor: Dr. Rainer Weiss

Title: Professor of Physics

Studies of Laser Interferometer Design and a Vibration Isolation System for Interferometric Gravitational Wave Detectors

by

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Submitted to the Department of Physics
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Doctor of Philosophy

Abstract

Two techniques are developed that are needed in the design of an interferometric gravitational wave (GW) detector such as the LIGO, or Long-baseline Interferometric Gravitational-wave Observatory. The detector sensitivity of a long-baseline instrument is studied.

A multi-layer mechanical isolation stack to filter seismic noise from test masses is designed, modeled and tested in vacuum. This is a four-stage elastomer (spring) and stainless steel (mass) stack, consisting of a table resting on three separate legs of three layers each. The visco-elastic properties of elastomer springs are exploited to damp the stack's normal modes while providing rapid roll-off of stack transmission above these modal frequencies. The stack's transmission of base motion to top motion is measured in vacuum and compared with 3-D finite-element models. In one tested configuration, at 100 Hz, horizontal transmission is 10^{-7}, vertical transmission is 3×10^{-6}, and the cross-coupling terms are between these values.

A length detection scheme using RF phase modulated light and synchronous detection is developed for Fabry-Perot arm power-recycled Michelson interferometer GW detectors. This scheme uses an external Mach-Zehnder interferometer to measure the GW signal, and a frequency-shifted subcarrier to measure ancillary interferometer degrees of freedom. Use of the Mach-Zehnder allows rejection of laser source amplitude noise from the output, as well as the ability to exploit well-balanced Fabry-Perot arms to reject frequency noise from the output.

A long baseline GW detector using these techniques should meet the LIGO initial goal sensitivity to GW strain of $h_{\mathrm{RMS}} = 10^{-21}$ at 100 Hz.

Thesis Supervisor: Rainer Weiss
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Signal Extraction and Control for an Interferometric Gravitational Wave Detector

Thesis by

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Abstract

Large interferometers are currently under construction for the detection of gravitational radiation. These will contain a number of optical surfaces at each of which the relative phase of incident beams must be kept strictly controlled in order to achieve high sensitivity.

The type of interferometer considered here consists of two Fabry-Perot cavities illuminated by a laser beam which is split in half by a beam splitter, together with a recycling mirror between the laser and the beam splitter, which reflects light returning from the beam splitter toward the laser back into the interferometer. A scheme for sensing deviations from proper interference has been analyzed and the adequacy of this method for incorporation in a control system has been evaluated. The sensing scheme involves phase modulating the laser light incident on the interferometer, introducing an asymmetry in the distances between the Fabry-Perot cavities and the beam splitter, and demodulating the signals from photodetectors monitoring three optical outputs of the interferometer. These optical outputs are light returning to the laser, light extracted by a pick-off from between the recycling mirror and the beam splitter, and light leaving the interferometer at the beam splitter.

The analysis has shown that the matrix of transfer functions from mirror displacement to demodulated signal is ill-conditioned, that as many as three of

the transfer functions may contain right half plane zeros, and that one of these transfer functions can be affected by the modulation depth. The performance of the closed-loop system, however, need not be significantly affected, provided that certain constraints are observed in the optical and electronic design.

A table-top interferometer has been constructed, to demonstrate the feasibility of constructing a control system using this sensing scheme and to compare the response of the interferometer with that predicted by calculations. Good agreement between the experiment and the calculation has been obtained.

Thermal Noise in the Initial LIGO Interferometers

Thesis by

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Abstract

Gravitational wave detectors capable of detecting broadband gravitational wave bursts with a strain amplitude sensitivity near 10^{-21} at frequencies around 100 Hz are currently under construction by the LIGO (Laser Interferometer Gravitational-wave Observatory) and VIRGO groups. One challenge facing these groups is how to detect the motion of the center of an inertial mass to a precision of 10^{-18} m when the mass consists of atoms each of which individually moves much more than that due to thermal energy. The uncertainty in the interferometer's measurement due to these thermal motions is called thermal noise. This thesis describes the thermal noise of the initial LIGO detectors.

The thermal noise was analyzed by modelling the normal modes of the test mass suspension system as harmonic oscillators with dissipation and applying the fluctuation dissipation theorem. The dissipation of all modes which contribute significant thermal noise to the interferometer was measured and from these measurements the total thermal noise was estimated.

The frequency dependence of the dissipation of the pendulum mode was characterized from measurements of the violin modes. A steel music wire suspension system was found to meet the goals of the initial LIGO detectors.

A mathematical technique was developed which relates the energy in each vibrational mode to the motion of the mirror surface measured by the interferometer. Modes with acoustic wavelengths greater than the laser beam spot size can contribute significant thermal noise to the interferometer measurements.

The dissipation of the test masses of LIGO's 40-m interferometer at Caltech was

investigated, and a technique for suspending and controlling the test masses which lowered the dissipation and met the thermal noise goals of the initial LIGO detector was developed. New test masses were installed in the 40-m interferometer resulting in improved noise performance.

The implications of thermal noise to detecting gravitational waves from inspiralling compact binaries was investigated. An optimal pendulum length for detecting these signals was found. It was shown that the narrow band thermally excited violin resonances could be efficiently filtered from the broadband gravitational wave signal.

Topics in General Relativity: naked singularities, and theoretical aspects of gravitational waves from merging compact binaries.

Thesis by
Theocharis A. Apostolatos

In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

California Institute of Technology
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Thesis Advisor:
Professor Kip S. Thorne

Abstract

Two topics in classical general relativity are discussed: a) The clothing of singularities by event horizons, and b) various issues in the evolution of coalescing compact binaries, as sources of gravitational waves to be detected by the LIGO/VIRGO/GEO ground-based detectors and/or the LISA space-based detector. More specifically:

We investigate a problem related to an important conjecture of classical relativity, namely the existence of a "cosmic censorship" that forbids the formation of naked singularities, and always clothes them with event horizons that causally hide them from the rest of the Universe. Under consideration is the role of rotation in an infinite cylindrical shell consisting of collisionless dust particles, half of which rotate clockwise and half counterclockwise. We show that, although such a shell without any rotation is known to collapse into a line singularity, the presence of an arbitrarily small amount of rotation is sufficient to halt the collapse. Such a shell, starting from a non equilibrium configuration, will "breath" radially, emitting gravitational waves, and will finally settle down to an equilibrium radius at which gravity is balanced by centrifugal forces. This suggests the essential role that rotation might play in halting the gravitational collapse of an elongated distribution of mass and preventing the formation of a naked singularity. However, this is a highly idealized example, and it can, by no means, ensure the validity of the "cosmic censorship" hypothesis.

On a separate topic, we explore the details of how gravitational radiation reaction drives the evolution of a slightly eccentric orbit of a small body around nonrotating supermassive black holes. A combination of analytic and numerical results arise from the solution of the Teukolsky perturbation equation. It is shown that in the fully relativistic situation, as in the Newtonian quadrupole approximation, there is a tendency for circularization of the orbit down to an orbital radius $r_c \simeq 6.6792GM/c^2$, where M is the mass of the black hole, and G and c are Newton's gravitation constant and the speed of light. It is further shown that for radii smaller than r_c the eccentricity increases.

Finally, an attempt is made to understand and construct analytic expressions that, based on the laws of general relativity, approximately describe the simultaneous precession in rapidly spinning black hole and/or neutron star and inspiral binaries with circular orbits. The precession is produced by general relativistic spin-orbit and spin-spin coupling; the inspiral, by gravitational radiation reaction. We derive the corresponding approximate waveforms to be received by the network of LIGO, VIRGO, and GEO earth-based gravitational-wave detectors. We then go on to investigate the adequateness of various "families of templates," to detect these spin-modulated waveforms by the method of "matching filters," We introduce a "fitting factor" FF as a measure of templates' adequateness, and show the complete inadequateness, for the task of detection, of the "Newtonian template family" (the set of the waveforms derived from the Newtonian, quadrupole approximation formalism). Another template family with an extra parameter is suggested that performs much better.

TOPICS IN GENERAL RELATIVITY: THE HOOP CONJECTURE, AND THEORETICAL ASPECTS OF GRAVITATIONAL WAVE DETECTION.

Thesis by
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Thesis Advisor:
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This thesis consists of four main chapters concerned with two topics in general relativity: the formation of horizons in nonspherical gravitational collapse (chapters 2 and 3), and aspects of the effort to detect gravitational waves from cosmic sources (chapters 4 and 5). More specifically:

Chapters 2 and 3 deal with a conjecture, put forward in the early 1970's by Kip Thorne, concerning the formation of black-hole horizons. This so-called hoop conjecture states, in effect, that an event horizon will form around a collapsing body of mass M when and only when the body becomes smaller than $\sim GM/c^2$ (i.e., smaller than its "gravitational radius") in all three spatial dimensions. As an example, the conjecture implies that a long thin spindle can contract radially to arbitrarily high densities without forming a horizon. We show in chapter 2 that some static, axisymmetric solutions to Einstein's equations are consistent with this conjecture. We also discuss which particular mathematically precise statements of the conjecture look plausible and which do not. Chapter 3 considers solutions of Einstein's initial value equations — in particular solutions which are momentarily static, conformally flat and axisymmetric. We show for solutions of the initial-value equations that, whenever the minimum value of the circumferences (or of the square roots of the areas) of all surfaces surrounding the source region is greater than a constant times the "ADM mass," then none of the level surfaces of the conformal factor can be "outer trapped." This result is along the lines of the hoop conjecture.

In chapter 4 we identify the optimal data analysis method for searching for a stochastic background of gravitational waves with a network of laser-interferometer gravitational-wave detectors, and we analyze the network's sensitivity to the background radiation, paying particular attention to how this sensitivity depends on the the orientations of the detectors. We show, for example, that a pair of detectors which subtends an angle at the center of the Earth of $\lesssim 70°$ should for optimum sensitivity have their arms make angles of 45° (modulo 90°) with the arc of the great circle that joins them. Detectors which are separated farther should instead have one arm each aligned with this arc. We also show that the minimum detectable stochastic energy-density for the LIGO pair of detectors, with their planned orientations, is $\sim 3\%$ greater than what it would be if the orientations were optimal, and is ~ 4 times what it would be if their separation were $\lesssim$ a few kilometers instead of the actual distance of $\sim 3000\,\mathrm{km}$. In the frequency range $20\,\mathrm{Hz} \lesssim f \lesssim 70\,\mathrm{Hz}$, the sensitivity level of the LIGO detector pair at an advanced stage of development will be roughly $\Omega_{gw} \sim 5 \times 10^{-10}$, which is about 4 orders of magnitude worse than the likely level of relic waves produced during inflation.

Chapter 5 explores the information that can be extracted, by LIGO and its European companion VIRGO, from the gravitational waves emitted by inspiralling neutron-star/neutron-star binaries, neutron-star/black-hole binaries, and black-hole/black-hole binaries. We show, for example, that from the inspiral waveforms: (i) a particular combination of the binaries' two masses will be measurable to within $\sim 0.1\% - 1\%$, (ii) the individual masses will be measurable to within $\sim 10\%$, and (iii) the distance to the source will typically be measurable to within $\sim 30\%$.

BLACK HOLES IN THE EARLY UNIVERSE, IN COMPACT BINARIES, AND AS ENERGY SOURCES INSIDE SOLAR-TYPE STARS

Thesis by
Dragoljub Marković

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Abstract

This thesis consists of three separate studies of roles that black holes might play in our universe.

In the first part we formulate a statistical method for infering the cosmological parameters of our universe from LIGO/VIRGO measurements of the gravitational waves produced by coalescing black-hole/neutron-star binaries. This method is based on the cosmological distance-redshift relation, with "luminosity distances" determined directly, and redshifts indirectly, from the gravitational waveforms. Using the current estimates of binary coalescence rates and projected "advanced" LIGO noise spectra, we conclude that by our method the Hubble constant should be measurable to within an error of a few per cent. The errors for the mean density of the universe and the cosmological constant will depend strongly on the size of the universe, varying from about 10% for a "small" universe up to and beyond 100% for a "large" universe. We further study the effects of random gravitational lensing and find that it may strongly impair the determination of the cosmological constant.

In the second part of this thesis we disprove a conjecture that black holes cannot form in an early, inflationary era of our universe, because of a quantum-field-theory-induced instability of the black-hole horizon. This instability was supposed to arise from the difference in temperatures of any black-hole horizon and the inflationary cosmological horizon; it was thought that this temperature difference would make every quantum state that is regular at the cosmological horizon be singular at the black-hole horizon. We disprove this conjecture by explicitly constructing a quantum vacuum state that is everywhere regular for a massless scalar field. We further show that this quantum state has all the nice thermal properties that one has come to expect of "good" vacuum states, both at the black-hole horizon and at the cosmological horizon.

In the third part of the thesis we study the evolution and implications of a hypothetical primordial black hole that might have found its way into the center of the Sun or any other solar-type star. As a foundation for our analysis, we generalize the mixing-length theory of convection to an optically thick, spherically symmetric accretion flow (and find in passing that the radial stretching of the inflowing fluid elements leads to a modification of the standard Schwarzschild criterion for convection). When the accretion is that of solar matter onto the primordial hole, the rotation of the Sun causes centrifugal hangup of the inflow near the hole, resulting in an "accretion torus" which produces an enhanced outflow of heat. We find,

however, that the turbulent viscosity, which accompanies the convective transport of this heat, extracts angular momentum from the inflowing gas, thereby buffering the torus into a lower luminosity than one might have expected. As a result, the solar surface will not be influenced noticeably by the torus's luminosity until at most three days before the Sun is finally devoured by the black hole. As a simple consequence, accretion onto a black hole inside the Sun cannot be an answer to the solar neutrino puzzle.