COINCIDENCE ANALYSIS OF GRAVITATIONAL WAVE DATA

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Declaration

I declare that this work has not already been accepted in any substance for any degree, and is not being currently submitted in candidature for any degree.

(Candidate)

Except where otherwise stated, this work is wholly the result of the candidate's own investigation. Suitable credit is given to joint work with colleagues, and to work of others throughout the thesis.

(Candidate)

(Supervisor)

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To my Father and Mother

Abstract

The work presented herein falls into three parts. Part I reassesses the claims recently made by the Rome-Turin-Maryland (RTM) collaboration, that about the time of Supernova SN1987A, there were unusual correlations observed between four particle detectors and two room-temperature bar gravitational wave detectors. These correlations were claimed to have chance probability of as low as $\sim 10^{-6}$. By evaluation of RTM's *a posteriori* adjustment of many free parameters, I revise the probability estimates up to between $\sim 10^{-3}$ and the level of chance. I conclude, in contradiction to RTM, that the correlations are more likely due to chance fluctuations in the data than to a new physical effect.

Part II is a short, mainly discursive, section. Here, I state many lessons which can be learned from RTM's analysis, with particular relevance to the coincidence analysis which I perform in Part III.

In Part III, I perform the first coincidence analysis of data taken from interferometric gravitational wave detectors, the data coming from a coincident experiment lasting 100 hours (the *100 Hour Data Run*) in March 1989, between the prototype detectors at the University of Glasgow and the Max-Planck-Institut für Quantenoptik, Garching. In particular, I present the first working program for the coincidence analysis of data taken from two interferometric detectors. I devise efficient methods for vetoing untrustworthy data, including the *h-veto*, which removes coincidences which have measured amplitudes differing by more than a predetermined amount in probability space.

After applying these vetoes, I show that there were no highly improbable coincidences during the experiment. I place the first experimental limits on 10 kHz broadband gravitational waves: no coincidences were seen above $h = (6.8 \pm 1.3) \times 10^{-16}$ during the experiment. I also present a way in which this limit could be improved for future similar experiments. Finally, I list the lessons learned from my coincidence analysis, for the interest of experimenters and data analysts in the field.

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Chapter 1

Introduction

Gravitational waves were theoretically predicted by Einstein in 1916, as a consequence of his general theory of relativity. Their existence is the most important remaining test of general relativity, and observation of gravitational waves will reveal much new astrophysics which will be interesting in its own right.

However, gravitational waves have not yet been convincingly detected, at the time of writing. Gravitational waves are very weak as a phenomenon; and at present, neither the detectors nor the data analysis systems are adequate to achieve reasonable observation rates. The solution of this detection problem and, later, the establishment of an observational science of gravitational wave astronomy, depends on attacking the problem from these two directions. On the one hand, one must build detectors which are sensitive enough. On the other hand, one must devise analysis methods and software to find the signals which may be there and, for the most part, to do this automatically and in real time.

With the next generation of detectors now being planned, we expect the increase in sensitivity obtained to facilitate the detection of gravitational waves by the end of the millenium. The overall system of data analysis also requires such an improvement. This thesis concerns itself with some of the remaining unsolved problems in the data analysis of gravitational waves. I hope it will contribute to the important first detection, when it happens; and, later, to the establishment of an observational science of gravitational wave astronomy.

1.1 Astrophysics of gravitational waves

1.1.1 Gravitational waves in general relativity

The field equations of general relativity, as derived by Einstein, are

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = kT_{\mu\nu}; \tag{1.1}$$

where $R_{\mu\nu}$ is the Ricci tensor, $R = R^{\mu}_{\mu} = g^{\mu\nu}R_{\mu\nu}$ is the trace of the Ricci tensor (the *Ricci scalar*), $g_{\mu\nu}$ is the metric tensor, $T_{\mu\nu}$ is the stress-energy tensor, and k is a constant. I use the following conventions:

- Strictly, $g_{\mu\nu}$ is not the metric tensor, but the (μ, ν) *component* of the metric tensor, normally denoted g; but I shall continue to use this lazy terminology. This also applies to the other "tensor" terms in the equation.
- The Greek indices μ, ν, etc. take values 0, 1, 2, 3. In flat space, I shall interpret these as the usual cartesian coordinates of special relativity, i.e. t, x, y, z, respectively.
- I use repetition of indices to indicate summation over the indices in question (the *summation convention*).

See, e.g. Schutz (1985) for more details. As is fairly standard for this calculation, I have ignored the cosmological constant term.

Consider the vacuum solution ($T_{\mu\nu} = 0$), and the weak field approximation, i.e.,

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \tag{1.2}$$

where $\eta_{\mu\nu}$ is the Galilean metric of flat spacetime, and $h_{\mu\nu}$ is a small perturbation, i.e. $|h_{\mu\nu}| << 1$. Now if we linearise and adopt the Lorentz gauge (see Schutz 1985), Eq. 1.1 becomes

$$\Box h_{\mu\nu} \equiv \left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right) h_{\mu\nu} = 0. \tag{1.3}$$

This is d'Alembert's equation. The most simple solution is

$$h_{\mu\nu} = \mathrm{Re}\left[A_{\mu\nu}e^{2\pi i(t-z/c)}\right], \tag{1.4}$$

that is, the equation of a three dimensional wave propagating through spacetime in the z direction, at the speed of light, c. This is a gravitational wave. We shall return to their effect on matter, and how they are to be detected, in a moment. Firstly, a quick review of expected astrophysical sources of gravitational waves.

1.1.2 Astrophysical sources of gravitational waves

Gravitational waves are produced by all matter which is moving with a non-zero quadrupole moment. How much energy is released, and whether the waves are observable from sources at astrophysical distances, is another question. Even the most energetic sources predicted will be very difficult to observe with Earth-based detectors, because gravitational waves generally couple very weakly with matter. At present, there are four main expected sources of gravitational waves which we expect will be observable in ground-based detectors. These are the following (for more details, see, e.g. Thorne 1987).

Stellar collapse

At the end of its life, a star will suffer one or more collapses, because its radiation and gas pressures can no longer sustain the star against its own inward gravitational pull. As the core of the star collapses, it can give off gravitational radiation. Although only one supernova every hundred years or so is expected in a galaxy of our size, there may be many more collapses which are *electromagnetically-quiet*, i.e. do not have dramatic supernova-type optical or electromagnetic displays, or which are hidden in or behind dense gaseous clouds. Current guesses at event rates are of the order of one collapse per thirty years in our galaxy.

Of course, if one can observe out to more distant galaxies and other clusters of galaxies, the event rate will go up in proportion to the volume of space observed, i.e. to the cube of the distance out to which one can observe these phenomena. The prototype detectors working in Glasgow and Garching (see Section 1.2), and whose data I analyse in coincidence (see Part III), could only barely detect a nearby collapse event in our galaxy; while the next generation of long interferometric gravitational wave observatories (such as LIGO and VIRGO), with their much increased sensitivities, are expected to see collapse sources out to the Virgo Cluster, with an expected event rate of around several hundred per year (Hough *et al.* 1989).

Coalescing compact binary stars

All binary stars, due to the non-zero quadrupole moment of their orbit, are gradually losing energy in the form of gravitational waves. This will cause the orbit to decay[1], such that even-

[1] as is seen directly in the pulsar PSR 1913+16, whose orbital period is decreasing in exactly the way predicted by general relativity, to the observational limit of 1% of the effect (the effect being that the rate

tually the stars will coalesce. Calculations for compact binaries (see e.g. Schutz 1986; Thorne 1987 and references therein) show that most of the observable gravitational wave energy is given off in the last few seconds, when the orbital frequency reaches 100 Hz and above. (The close orbit of gaseous stars is much more difficult to simulate, due to hydrodynamics and tidal effects.)

Although the expected event rate for coalescing binaries in our galaxy is very low, compared to collapse event rates, the fact that one can fairly accurately predict the waveform of binary coalescence enables one to employ data analysis techniques, such as matched filtering, to improve the signal-to-noise ratio for a given detection; and hence to see objects much further away than would otherwise be the case. Hence, the observed event rate may be comparable to that of collapse events; but this is model-dependent (see Phinney 1991).

Continuous wave sources

Any rapidly rotating object will emit gravitational waves, if it has a non-zero quadrupole moment. Rapidly rotating neutron stars are the most famous candidate sources of this type of gravitational radiation. In order for them to emit, however, they must have some kind of non-axisymmetry (the axis in question being the rotation axis) due to either "geophysical" deformations (such as mountains) or large scale eccentricity of shape (e.g. caused by mechanical instabilities or magnetic effects). In this case, the expected wave form will be a sine wave, or several sine waves superimposed in the case of several non-axisymmetric imperfections in the shape of the body.

The expected amplitude of waves from such a source will be much lower again than for coalescing binaries; but the very long period of possible observation (up to years, interruptions being unimportant so long as the phase is preserved), coupled with our knowledge of the waveform, will enable observations of many sources in our galaxy with the long interferometers, operating in broadband. The main unsolved problem here in the data analysis is the inversion of the Doppler motion of the Earth, which is unknown *a priori* when the rotation frequency and location of the source on the sky are unknown. Some attempts have been made to solve this problem: see e.g. Schutz (1991).

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of change of the orbital period, $\dot{P}_b = -2.43 \times 10^{-12}$ s s^{-1}). See Taylor & Weisberg 1989. This is almost conclusive observational evidence that gravitational waves exist, and are emitted at energies predicted by general relativity.