Gravitational waves from accreting neutron stars and Cassiopeia A

by
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Declaration

This thesis is an account of research undertaken between March 2005 and October 2009. The research was conducted within the Centre for Gravitational Physics at the Australian National University, and during visits to the LIGO Hanford Observatory, the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), the University of Melbourne, and the Pennsylvania State University.

The research described in this thesis is my own work, except where otherwise indicated. Research that has been conducted in collaboration with colleagues is explicitly acknowledged as such. Appropriate references to the work of others are included throughout.

To the best of my knowledge, the work presented in this thesis is original, and has not been submitted for a degree at any university.

Karl W. Wette
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In loving memory of my grandparents:

Nana Joan and Poppa Jack,

Oma Erna und Opa Jobst

Abstract

This thesis is concerned with the mysteries of neutron stars and the quest for gravitational waves. Rapidly-rotating neutron stars are anticipated sources of periodic gravitational waves, and are expected to be detectable within the next decade using kilometre-scale laser interferometry.

We first perform ideal-magnetohydrodynamic axisymmetric simulations of a magnetically confined mountain on an accreting neutron star. Two scenarios are considered, in which the mountain sits atop a hard surface or sinks into a soft, fluid base. We quantify the ellipticity of the star, due to a mountain grown on a hard surface, and the reduction in ellipticity due to sinking. The consequences for gravitational waves from low-mass x-ray binaries are discussed.

We next present two approaches to reducing the computational cost of searches for periodic gravitational waves. First, we generalise the PowerFlux semi-coherent search method to estimate the amplitudes and polarisation of the periodic gravitational wave signal. The relative efficiencies of the generalised and standard methods are compared using simulated signals. Second, we present an algorithm which minimises the number of templates required for a fully coherent search, by using lattice sphere covering to optimally place templates in the search parameter space. An implementation of the algorithm is tested using Monte Carlo simulations.

Finally, we present a coherent search for periodic gravitational waves targeting the central compact object in the supernova remnant Cassiopeia A, using data from the fifth science run of the Laser Interferometer Gravitational-Wave Observatory. The search parameter space is determined by the sensitive frequencies of the detectors, by the age of the compact object, and a range of braking indices. No gravitational wave signal is detected. We set an upper limit on the strength of gravitational waves from the compact object in Cassiopeia A, which surpasses the theoretical limit based on energy conservation. Cassiopeia A is thus one of only a few astronomical objects, to date, where gravitational wave observations are beginning to constrain astrophysics.

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Chapter 1

Introduction

This thesis is concerned with two exciting arenas of modern physics: neutron stars, and gravitational waves. Since the beginning of the twentieth century, experiments have been conducted, with increasing precision, to probe the nature of gravity, and to test the predictions of its most successful theory: the general theory of relativity. Gravitational waves, predicted by the theory, are the next frontier of experimental gravity, and a first direct detection is widely anticipated within the next decade. Meanwhile, the existence of neutron stars has been confirmed by the discovery of pulsars, which have been studied in detail over the last half-century. Neutron stars are important gravitational wave sources; in turn, gravitational wave astronomy offers the possibility of gaining further insights into neutron star physics. Chapter 2 introduces the physics of neutron stars and gravitational waves, and discusses one important link between them.

Chapters 3–4 are concerned with the physics of accreting neutron stars. Specifically, we investigate the formation by the accreted matter of a mountain on the stellar surface, held in a stable equilibrium by the star's powerful magnetic field. The burial of the magnetic field by the accreted mountain can explain why the magnetic field of a neutron star reduces as the star accretes, which is important for models of the evolution of binary pulsar systems. Magnetic mountains are also a plausible means of generating gravitational radiation from low-mass x-ray binaries. The effect of the magnetic mountain sinking into the neutron star crust has not been accounted for in previous work, and is the key advance of the work presented here.

In Chapter 3, we review previous work on this problem, and present a numerical procedure capable of building magnetic mountains with realistic masses. In Chapter 4, we present a detailed comparison of two scenarios, where the magnetic mountain either sits atop a hard surface or sinks into a soft, fluid base. We discuss the evolution of a magnetic mountain during accretion, and compare the hydromagnetic structures of mountains grown on hard and soft bases. We allow the mountain to sink in two different but theoretically identical scenarios, and confirm that the resultant equilibria are equivalent. We quantify the ellipticity of the neutron star, due to a mountain grown on a hard surface, and the reduction in ellipticity due to sinking. Finally, we compare our simulations to the model of Choudhuri & Konar (2002), and discuss the consequences for gravitational waves from low-mass x-ray binaries.

Chapters 5–9 are concerned with gravitational waves, and the challenge of analysing the output of kilometre-scale laser interferometric detectors in search of their signatures. In Chapter 5, we summarise results from the searches for gravitational waves conducted to date. We then review the analysis of periodic gravitational waves, which are anticipated to be generated by rapidly rotating neutron stars. We present the analytic model of the periodic gravitational wave signal, the coherent matched filtering technique used to search for them, and discuss the computational cost of such searches. We then explore, in Chapters 6–7, two different approaches to lowering the computational cost of periodic gravitational wave searches.

In Chapter 6, we consider semi-coherent search techniques. Compared to fully coherent matched filtering, these techniques are less sensitive, but are also less computationally intensive; as a result, they can achieve greater overall sensitivity by searching longer stretches of data than would be computationally feasible using a coherent method. We consider the PowerFlux semi-coherent method, and present an alternative derivation to that of Dergachev & Riles (2005). We then generalise the PowerFlux method to estimate the amplitudes of the plus and cross polarisations, and the polarisation angle of the periodic gravitational wave signal. Using simulated signals injected into Gaussian noise, we compare the parameter estimation and detection efficiencies of the generalised and standard PowerFlux methods.

In Chapter 7, we present an algorithm which generates a bank of templates for a coherent search over a given template parameter space. The algorithm is designed to minimise the number of templates required to cover the parameter space, thus minimising the computational cost of the search, while ensuring that any potential signal will still be closely matched by some template in the bank. The algorithm uses sphere coverings on optimally thin lattices to position the points in the parameter space, and a metric on the parameter space to ensure the correct spacing. Particular care is taken to generate extra templates along the edges of the parameter space to ensure that they are completely covered. The chapter introduces the necessary background material, presents the algorithm, discusses how to estimate the number of templates the algorithm requires for coverage, and tests the performance of an implementation of the algorithm.

Finally, in Chapters 8–9, we present a search for periodic gravitational waves targeted at the central compact object in the supernova remnant Cassiopeia A. The compact object is likely the youngest known neutron star, and has been widely studied by astronomers since its discovery a decade ago. No pulsations are observed from the compact object, and it therefore has no known spin frequency. The search uses data from the fifth science run (S5) of the Laser Interferometer Gravitational-Wave Observatory (LIGO), and is the first gravitational wave search to target a known non-pulsing neutron star. An indirect upper limit on the strength of gravitational waves from the compact object can be beaten, over a range of frequencies, using a coherent search of 12 days of LIGO S5 data. Cassiopeia A is therefore one of the few periodic gravitational wave sources which could conceivably be seen by LIGO at its present sensitivity.

In Chapter 8, we review electromagnetic observations of Cassiopeia A, and the motivation for a gravitational wave search. We derive the indirect upper limit on the compact object, and present details of the proposed search, including the choice of analysis method and the time span of the data set, the parameter space of frequencies and frequency derivatives to be searched, and its estimated sensitivity. We confirm that the search will beat the indirect upper limit, and is computationally feasible. Chapter 9 presents the implementation of the search, which includes the selection of data from the LIGO S5 run, the execution of the search pipeline, and post-processing procedures to remove false candidates arising from instrumental noise. After performing these steps, we find that there is no evidence for the detection of a gravitational wave signal from Cassiopeia A. We then determine upper limits on the strength of gravitational waves from Cassiopeia A which, as expected, beat the indirect limit over the range of frequencies searched. Cassiopeia A is one of only a handful of astronomical objects for which this has been achieved.

Chapter 10 summarises the thesis and considers possible directions for further research.

1.1 Author contributions and publications

While this thesis is substantially the work of the author, it also includes work that was done in collaboration with colleagues. This section describes in full the contributions made by the author to the research presented in each chapter, and any publications on which the chapter is based.

Chapter 2 reviews background information relevant to the thesis as a whole.

Chapters 3–4 present work done in collaboration with Andrew Melatos and Matthias Vigelius (University of Melbourne). The two chapters are closely based on the following publication:

Wette *et al.* (2010):
K. Wette, M. Vigelius, and A. Melatos, 2010. Sinking of a magnetically confined mountain on an accreting neutron star. *Monthly Notices of the Royal Astronomical Society* 402, 1099.

Chapter 5 reviews background information relevant to Chapters 6–9.

Chapter 6 presents work done in collaboration with Gregory Mendell (LIGO Hanford Observatory). The chapter is closely based on the following publication:

Mendell & Wette (2008):
G. Mendell and K. Wette, 2008. Using generalized PowerFlux methods to estimate the parameters of periodic gravitational waves. *Classical and Quantum Gravity* 25(11), 114044.

Chapter 7 presents the work of the author, and has not been published.

Chapters 8–9 present work conducted within the LIGO Scientific Collaboration (LSC). The LSC works alongside the LIGO Laboratory to undertake the science of LIGO. This includes operating the Observatory's twin gravitational wave detectors during data acquisition, monitoring the detectors' performance to ensure the acquired data is of science quality, the correct calibration of the raw detector output, the generation of derived data products from the raw output, authoring the scientific software used in the analysis of the data, and the operating and maintaining of large-scale computer clusters on which the analyses are performed.

Author contributions The author participated in the acquisition of LIGO data by serving as a science monitor at the LIGO Hanford Observatory. The author held primary responsibility for conducting the search for periodic gravitational waves from the supernova remnant Cassiopeia A presented in Chapters 8–9. This included deciding on the various parameters of the search, the design and authoring of the template bank generation algorithm described in Chapter 7, authoring scripts to manage the search pipeline, submitting and managing search jobs on computer clusters, designing and executing the post-processing of the results, and determining the upper limits. The author greatly benefitted from discussions, at regular teleconferences and at face-to-face meetings, with colleagues in the Continuous Wave (CW) Working Group of the LSC. The author was also responsible for presenting the search to the CW Review Committee, which approved the presentation of preliminary results at the 8th Edoardo Amaldi Conference on Gravitational Waves. The same results are reproduced in this thesis.

Publications Chapters 8–9 expand upon the following publications:

Wette *et al.* (2008):
K. Wette, B. J. Owen, B. Allen, M. Ashley, J. Betzwieser, N. Christensen, T. D. Creighton, V. Dergachev, I. Gholami, E. Goetz, R. Gustafson, D. Hammer, D. I. Jones, B. Krishnan, M. Landry, B. Machenschalk, D. E. McClelland, G. Mendell, C. J. Messenger, M. A. Papa, P. Patel, M. Pitkin, H. J. Pletsch, R. Prix, K. Riles, L. S. de la Jordana, S. M. Scott, A. M. Sintes, M. Trias, J. T. Whelan, and G. Woan, 2008. Searching for gravitational waves from Cassiopeia A with LIGO. *Classical and Quantum Gravity* 25(23), 235011.

Abadie *et al.* (2010):
J. Abadie *et al.* (LIGO Scientific Collaboration), 2010. First search for gravitational waves from the youngest known neutron star. *The Astrophysical Journal* in press.

Disclaimer The search for Cassiopeia A is, at the time of writing, under internal review within the LSC; the material presented in Chapters 8–9 is therefore subject to change. The views and opinions expressed in this thesis regarding the Cassiopeia A search are those of the author, and do not necessarily reflect the views and opinions of the LSC.

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