A Directed Search for Continuous Gravitational Waves from Unknown Isolated Neutron Stars at the Galactic Center

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Zusammenfassung

Gravitationswellen gehören zu den zentralen Vorhersagen der Einstein'schen Allgemeinen Relativitätstheorie. Durch ihre direkte Messung könnten auf einzigartige Weise die treibenden Kräfte hochenergetischer, astrophysikalischer Ereignisse erforscht werden. Doch aufgrund ihrer schwachen Wechselwirkung mit Materie ist bisher kein solcher Nachweis gelungen.

Diese Arbeit präsentiert die bislang erste Suche nach kontinuierlichen Gravitationswellen von unbekannten Neutronensternen im Zentrum unserer Galaxie. Für die Suche wurden fast zwei Jahre Daten zweier LIGO Detektoren aus dem fünften Science Run ausgewertet. Das galaktische Zentrum wurde ausgewählt weil die hohe Anzahl vorhandener massereicher Sterne, die nach heutigen Kenntnissen die Vorgänger von Neutronensternen sind, einen Überfluss an Neutronensternen selbst im Zentrum der Galaxie verspricht.

Da dies eine blinde Suche ist muss ein enormer Parameterraum berücksichtigt werden. Dieser stellt die Hauptschwierigkeit dar: durch den großen Frequenzbereich und den entsprechenden Bereich in erster Ableitung ist die Sensitivität selbst für eine einzelne Himmelskoordinate durch die verfügbare Rechenleistung limitiert. Eine Optimalfilter-Suchtechnik über angemessen lange Beobachtungszeiten würde die beste Sensitivität erzielen, ist aber zur heutigen Zeit und in absehbarer Zukunft mit den verfügbaren Rechenkapazitäten nicht möglich. Daher wird eine Methode verwendet, bei der zunächst 630 einzelne, 11.5 Stunden lange Datensegmente kohärent analysiert werden. Im Anschluss werden die Einzelergebnisse inkohärent kombiniert. Dieser Vorgang ermöglicht es einen Gravitationswellenfrequenzbereich von 78 bis 496 Hz und einen Bereich in erster Ableitung, der definiert ist durch $\dot{f} = -f/200$ yr, abzudecken.

Es wurde kein Gravitationswellensignal entdeckt. Daher werden 90% Konfidenz-Obergrenzen auf die Gravitationswellenamplitude für Quellen im galaktischen Zentrum angegeben. Dies sind die bislang einschränkendsten existierenden Grenzen einer Suche nach kontinuierlichen Gravitationswellen mit einem derart großen Parameterraum.

Schlagworte: *Gravitationswellen, Datenanlyse, Galaktisches Zentrum*

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Abstract

Gravitational waves are one of the key predictions of Einstein's Theory of General Relativity. Direct observation of gravitational waves would allow us to probe the engines for highly energetic astrophysical events. However, since gravitational waves interact very weakly with matter, there have been no direct observations to date.

In this work the results of a directed search for continuous gravitational waves from unknown, isolated neutron stars at the Galactic Center, performed on almost two years of data from the fifth Science Run from two LIGO detectors are presented. The Galactic Center is believed to host an abundance of neutron stars that is reflected by the high number of massive stars known to be present in this area. According to current evolutionary scenarios, massive stars are the progenitors of neutron stars.

The main obstacle is the enormous parameter space that has to be searched over. Even for known sky positions the search sensitivity is computationally limited, because a large range in frequency and one or more frequency derivatives has to be covered, depending on the age of the potential source. A coherent optimal matched filter search for realistically long observation times would gain the highest sensitivity, but is not computationally feasible at the present time, or in the foreseeable future. Therefore, one requires methods which are computationally inexpensive, at the cost of being somewhat less sensitive. The search uses a semi-coherent approach, coherently analyzing 630 segments, each spanning 11.5 hours, and then incoherently combining the results of the single segments. It covers gravitational wave frequencies in a range from 78 to 496 Hz and a range of first order spindown values corresponding to $\dot{f} = -f/200$ yr.

No gravitational waves were detected. Therefore, 90% confidence upper limits on the gravitational wave amplitude of sources at the Galactic Center are placed, which are the most constraining to date for a large-parameter-space search for continuous gravitational wave signals.

Keywords: *Gravitational Waves, Data Analysis, Galactic Center*

Contents

All great achievements require time.

Maya Angelou

1 Introduction

For more than 50 years, scientists have been attempting to directly detect gravitational waves. Although the knowledge of their existence is the result of formal mathematical reasoning, different astrophysical scenarios have been developed to predict where these waves are emitted and indirect evidence of their existence could be achieved [119]. The best hope for detecting gravitational waves involves large masses moving with near-relativistic speeds and accelerations. Unlike the experiment Hertz did in 1888 to prove the existence of electromagnetic waves predicted by Maxwell, generating electromagnetic waves and detecting them instantly, laboratory generation of detectable gravitational waves is impossible.

In the past several years gravitational wave detectors have undergone major improvements in their sensitivity and duty factor. This is important because the sensitivity of the detectors is a limiting factor for the reach of gravitational wave searches. Another way to improve the sensitivity lies in the development of sophisticated analysis techniques to process the recorded data. The particulars of a specific analysis method depend critically on the expected waveform of the gravitational wave signal.

This work is concerned with *continuous* gravitational waves, emitted by young, rapidly rotating neutron stars. The waveform of such waves is a nearly monochromatic sinusoid that changes frequency very slowly over time. These waves are emitted over long timescales, typically much longer than the observation time. One way in which a neutron star can emit continuous gravitational waves is if its shape deviates from axial symmetry, for example if it exhibits a small "mountain" on its surface. As the star spins, this generates a time-varying quadrupole moment of inertia which, in turn, generates gravitational waves.

A variety of searches for continuous gravitational waves from neutron stars have been performed. Some searches have aimed to detect signals from known objects [33], like the low-mass X-ray binary Scorpius X-1 [23, 24], the Cassiopeia A central compact object [7], and the Crab and Vela pulsars [12, 26, 28]. Besides the known objects, extensive all-sky searches have been performed in recent years [3, 16, 22, 25, 27, 29, 30]. This work presents the first directed search for continuous gravitational waves from unknown, isolated neutron stars at the Galactic Center. The term Galactic Center is used here as a synonym for the sky coordinates of Sagittarius A* (Sgr A*). Out of about 2000 known pulsars, five are located within ~ 240 pc of Sgr A*[77] of which three are within ~ 24 - 36 pc of Sgr A*[56]. The existence of these five pulsars supports the belief that the Galactic Center might harbor a large population of pulsars not apparent to radio surveys because of the dispersion of the radio signal by dust or ionized plasma along the line of sight. Current stellar evolutionary models predict that neutron stars are born in supernova explosions of massive stars [61]. At least three stellar clusters in the Galactic Center region contain massive stars, potential progenitors of neutron stars [56].

A primary obstacle in searches like the one presented in this work is the small amplitude of the putative gravitational wave signal. Long observation times of order months to years are required to detect a signal above the noise. When the frequency and frequency evolution of the potential objects are unknown, the parameter space to search is large. A coherent search that uses matched filtering of the data against single templates over long observation times and covering a large parameter space is computationally infeasible. To overcome this limitation, techniques have been developed to maximize the attainable sensitivity at fixed computing cost. This search uses a *hierarchical search technique* [51, 97] consisting of a coherent step over short duration data segments, using a maximum-likelihood statistic [55, 76], that is then followed by an incoherent combination of the results from the coherent step [52]. This allows the analysis to cover a wide range of different signals, defined by the frequency and the frequency derivative (spindown). No other search for signals from unknown neutron stars has ever considered as large a range in spindown values as this search.

The large parameter space is one of the strengths of this search. Another strong point is the elaborate post-processing that allows one to consider candidates with significance values three standard deviations below the expectation value for pure Gaussian noise. A huge number of candidates is tested by a series of vetoes.

No search has yet resulted in the detection of a gravitational wave signal. However, the absence of a detection allows one to draw conclusions on the maximum possible strength of continuous gravitational waves from the searched population. The current most sensitive upper limit on the gravitational wave strain amplitude for sources in the direction of the Galactic Center comes from the all-sky searches and is (with 90% confidence) $h_0 = 7.6 \times 10^{-25}$ [3]. The search presented here improves the limits of [3] by about a factor of two and presents the most constraining upper limits ever set in a large parameter space search like this.

Outline

The outline of the thesis is as follows: the first chapters give a broad overview of the various aspects that, all together, provide the basis for a gravitational wave search. First, a brief description of gravitational waves in the Theory of General Relativity is given, followed by an introduction on neutron stars and pulsars and the Galactic Center (Chapter 2). Chapter 3 is an overview of gravitational wave detectors and their basic method of operation. The last of the introductory chapters illustrates the main principles of the data analysis methods, derives the detection statistic and presents the concept of the search technique used for this search (Chapter 4). In Chapter 5 the preparation of the search, the setup of the covered parameter space, and the selection of the data segments are presented. The various stages of post-processing and a coherent follow-up search are presented in Chapter 6. No candidate is confirmed by the follow-up. Therefore, 90% confidence upper limits are placed on the gravitational wave amplitude (Chapter 7). In subsequent Chapter 8 a thorough discussion of the implication of the fact that no second time derivative of the frequency was considered in this search is given. Finally, the results and their implications are discussed in Chapter 9.