Investigation into the Millihertz Gravitational Wave Spectrum: Models and Observation Techniques for Sources Using the Laser Interferometer Space Antenna (LISA)

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Abstract

Ground-based detection of gravitational-wave sources has become a reality, but the full potential of gravitational-wave astronomy will only be realized with access to the source-rich millihertz frequency band, which future space-based detectors like LISA (Laser Interferometer Space Antenna) are set to provide. The modeling of LISA sources and their extraction from noisy data present unique, challenging, and under-explored problems. A comprehensive roadmap for resolving these issues needs to be developed as the ESA-led mission approaches formal adoption in the early 2020s. The groundbreaking direct detection of gravitational waves (GWs) by Advanced LIGO in September 2015 marked a pivotal moment, establishing GW astronomy as a transformative tool for exploring the universe. Shortly after, the LISA Pathfinder mission demonstrated the technological feasibility of detecting GWs from space, paving the way for space-based

interferometers like LISA to explore lower-frequency GW signals and uncover a richer variety of sources. However, significant challenges must be overcome to unlock the scientific potential of millihertz GW astronomy. Analyzing data from space-based detectors presents extreme technical difficulties. As LISA moves closer to being officially selected by the European Space Agency for its Cosmic Vision science programme's L3 mission, it is critical to address several pressing issues related to data analysis in the coming years. These efforts will not only guide the mission's design but also ensure its successful implementation. Two central challenges stand out: first, the lack of sufficiently accurate yet computationally efficient models for capturing the intricate waveforms generated by LISA sources; and second, the need for sophisticated algorithms capable of identifying and characterizing a vast array of sources within noisy datasets. Unlike ground-based detectors, LISA is expected to observe numerous long-lived sources. These include binary systems involving stellar-origin compact objects (such as white dwarfs, neutron stars, or stellar-mass black holes), mergers between supermassive black holes (SMBHs) found at galactic centers, and extreme mass-ratio inspirals (EMRIs), where compact objects spiral into such massive black holes. Observing these sources through GWs will complement electromagnetic observations, shedding light on the formation rates and evolutionary paths of compact binaries within the Milky Way and SMBHs in galactic nuclei. For SMBH mergers and EMRIs in particular, LISA will enable unprecedented precision measurements of strong-field gravity. [1-70]

Keywords: Energy Transfer, Thermodynamics, LISA Laser Interferometer Space Antenna, Laser Interferometer Gravitational-Wave Observatory (LIGO), Gravitational Wave, super- massive black holes (SMBHs, Black-Hole Thermodynamics, Milky Way Galaxy, Extreme-mass- ratio inspirals (EMRIs), Quantum Thermodynamics

Introduction

Ground-based observations of gravitational-wave sources have become a reality, marking a significant achievement in astronomy. However, the full potential of gravitational-wave science can only be realized with access to the millihertz frequency band, which is rich in potential sources. This access is expected to be provided by future space-based detectors like the Laser Interferometer Space Antenna (LISA). The successful modeling of LISA sources and their extraction from noisy datasets involves numerous complex challenges that are still insufficiently explored. Therefore, a comprehensive plan must be established to address these issues before the European Space Agency formally adopts the mission in the early 2020s. The milestone moment for gravitational-wave astronomy began in September 2015, with the first direct detection of gravitational waves by Advanced LIGO. This breakthrough revealed a promising path to studying the universe in a new way. Shortly thereafter, the LISA Pathfinder mission demonstrated the feasibility of observing gravitational-wave sources from space, paving the way for future space-based detectors like LISA to explore low-frequency gravitational waves and access a more diverse range of cosmic sources. Achieving the goals of millihertz gravitational-wave astronomy requires overcoming significant obstacles in data analysis for space-based detectors. With LISA set to become part of ESA's Cosmic Vision programme as the gravitational-focused L3 mission, urgent steps must be taken to address key data analysis challenges over the next few years. These efforts will play a crucial role in refining mission designs and preparing for their eventual implementation. Two major aspects demand attention: first, the development of computationally efficient and highly accurate models for the intricate waveforms produced by LISA sources; second, the creation of advanced algorithms capable of identifying numerous gravitational-wave signals buried within noisy data and characterizing their astrophysical features. These tasks are essential to unlocking the scientific potential of millihertz observations. Unlike ground-based detectors, LISA is expected to detect a wealth of long-duration gravitational-wave signals. These include binary systems composed of stellar-origin compact objects like white dwarfs, neutron stars, or stellar-mass black holes; mergers between supermassive black holes found at galactic centers; and extreme-mass-ratio inspirals, where compact objects spiral into supermassive black holes. Observations of these sources will significantly enhance our understanding of compact binary formation rates, evolutionary phenomena in the Milky Way, and supermassive black holes in galaxy cores. Moreover, SMBH mergers and EMRIs will allow unprecedented measurements of strong-field gravity, complementing electromagnetic studies and providing profound insights into cosmic phenomena.[1-70]

Material, Method, Discusssion

The current research on gravitational waves is outlined as follows: [1-70]

- Bayesian model selection: Explored applications of gravitational waves to a sampling method aimed at accelerating Bayesian model selection processes. This approach was tested on a simplified waveform model incorporating parametrized phase deformations and proven effective for sampling the standard gravitational-wave likelihood. Conducted at the University of Cambridge during 2016–2017 in collaboration with Sonke Hee, Mike Hobson, Anthony Lasenby, and others. [1-70]

-Tests of general relativity: Examined the extent to which black-hole solutions in general relativity can be validated using observations from LISA. Developed waveforms for extreme-mass-ratio inspirals within modified-gravity spacetimes and performed preliminary studies on parameter estimation using these waveforms. This research was carried out at Cambridge in 2016–2017 with Christopher Moore (Cambridge) and Jonathan Gair (University of Edinburgh). [1-70]

-Eccentric binary mergers: Focused on modeling orbital eccentricities in binary systems comprising comparable masses. Enhanced the merger and ringdown phases of a rapid eccentric waveform model by leveraging numerical-relativity waveform interpolation. Conducted at Cambridge during 2016–2017 alongside Eliu Huerta (UIUC), Harald Pfeiffer, Prayush Kumar (Canadian Institute for Theoretical Astrophysics), and others. [1-70]

-Extreme-mass-ratio inspirals: Worked on improving kludge waveform models for extreme-mass-ratio inspirals. Made modifications such as adding a frequency map to a commonly used analytic waveform, which originally dephased within hours compared to more precise waveforms. The enhanced waveform remains phase-coherent for months without incurring additional computational costs. A public software suite implementing this augmented waveform has been released in preparation for upcoming mock LISA data challenges (github.com/alvincjk/EMRI_Kludge_Suite). This research was conducted at Cambridge between 2015 and 2017 in partnership with Jonathan Gair. [1-70]

-Gaussian process regression: Investigated the potential of Gaussian process regression, a machine learning technique, for analyzing gravitational-wave data. Constructed a Bayesian likelihood using Gaussian process regression to account for theoretical errors while maintaining computational efficiency. Applied the method to estimate the chirp mass in binary mergers of comparable sizes, accelerating the learning phase of Gaussian process regression and testing these approaches across both synthetic and real data sets. Conducted at Cambridge from 2015 to 2017 in collaboration with Christopher Moore, Christopher Berry (University of Birmingham), and Jonathan Gair. [1-70]

Previous studies on gravitational waves include the following: [1-70]

- Template bank compression: This research explored methods to reduce the online computational cost of matched-filter searches using waveform template banks. Various tunable compression schemes were proposed and evaluated, demonstrating faster signal detection and localization through offline compression while maintaining improved sensitivity and accuracy compared to coarsened banks at equivalent computational costs. The most effective compression scheme was applied to a large template bank of realistic waveforms to validate its practicality. This study was conducted at Cambridge between 2014 and 2015, in collaboration with Jonathan Gair. [1-70]

- Gravitational-electromagnetic interactions: This work examined the interaction between gravitational waves and electromagnetic fields using the 1+3 relativity framework. It rederived the inverse Gertsenshtein conversion, revealing its potential significance for highly magnetized pulsars in compact binary systems. Weak yet distinguishable interference effects between gravitational and electromagnetic waves were identified, while disproving the existence of previously suggested wave-wave resonances. The research was conducted at Cambridge from 2013 to 2014 with Priscilla Canizares (Radboud University) and Jonathan Gair. [1-70]

Other theoretical physics research includes: [1-70]

- Superfluid vacuum theory: This investigation analyzed superfluidity and quantized vorticity within complex scalar fields in rotating spacetimes, showing through numerical simulations that vortex nucleation can originate from the angular momentum of spacetime itself. The study took place at Nanyang Technological University (NTU) in 2013 with Michael Good (Nazarbayev University), Chi Xiong (NTU), and Kerson Huang (MIT). - Conformal cosmology: This study explored how the conformal framework for quiescent cosmology and the Weyl curvature hypothesis could be enhanced by incorporating spacetime self-similarity. The research introduced a geometric definition of asymptotic self-similarity and derived practical results demonstrating its relevance within this cosmological framework. Conducted at the Australian National University (ANU) in 2012, the study involved Susan Scott (ANU). [1-70]

- Mirror dark matter: This research assessed the feasibility of an alternative dark matter model, comparing mirror dark matter and cold dark matter theories in terms of their predictions regarding stellar orbits in the Milky Way and other disk galaxies. The results showed how the mirror dark matter theory could be disproven through observations of stellar escape speeds. This work was carried out at ANU between 2011 and 2012 with Dayal Wickramasinghe and Lilia Ferrario (ANU). [1-70]

- Quantum-classical hybrid theory: This analysis focused on a hybrid theory that integrates interacting quantum and classical ensembles. Numerical solutions for squeezed coherent states of harmonically coupled oscillators were derived, revealing unique behaviors that make it possible to distinguish this theory experimentally from standard quantum mechanics. The research was conducted at ANU from 2010 to 2011 in collaboration with Michael Hall (Griffith University) and Craig Savage (ANU). [1-70]

Conclusion

This research aims to utilize the acquired skills and knowledge for investigating LISA sources and enhancing data analysis techniques. It will play a crucial role in supporting LISA's scientific and technological advancements while contributing to the global effort of demonstrating its ability to produce groundbreaking scientific results. Additionally, significant interest exists in exploring how LISA can serve as a transformative tool in probing fundamental aspects of physics, astrophysics, and cosmology. Current investigations are focused on assessing the validity of black-hole solutions in general relativity through LISA observations, with parameter estimation studies being performed on waveforms from EMRIs within modified-gravity frameworks. [33, 34] The methodologies and tools developed during this fellowship intend to unlock novel approaches to scientific inquiry with LISA, while refining classic challenges such as determining the SMBH mass function or precisely measuring the Hubble constant. [35, 36] Furthermore, although this proposal primarily emphasizes millihertz gravitational waves (GWs), numerous techniques discussed can be adapted for broader astronomical applications across the GW spectrum. Active and future collaborations within various research communities are expected to facilitate cross-disciplinary innovation and shared technological advancements. As an ongoing participant in the LIGO Scientific Collaboration, efforts will continue to refine data analysis methods applicable to both LISA and ground-based interferometers operating in the kilohertz band. There is also growing interest in pulsar timing arrays and their ability to detect nanohertz GW sources. With a strong NANOGrav presence at JPL, including collaborations with experts opportunities for working alongside pulsar timing researchers are anticipated, particularly concerning Bayesian inference techniques. [1-70]

BIOGRAPHY OF AUTHOR:

Asst. Prof. Dr. Dipl.-Ing. Emin Taner ELMAS

Asst.Prof. Dr. Emin Taner ELMAS is a Mechanical Engineer having degrees of B.Sc., M.Sc., Ph.D., and was born in Sivas in 1974. He completed his doctorate at Ege University, Graduate School of Natural and Applied Sciences, Mechanical Engineering Department, Thermodynamics Science Branch, and his master's degree at Dokuz Eylül University, Mechanical Engineering Department, Energy Science Branch. He also completed his undergraduate education at Hacettepe University, ZEF, Mechanical Engineering Department and graduated from the faculty with honors in 1995 and became a mechanical engineer. He was awarded a non-refundable scholarship by the Turkish Chamber of Mechanical Engineers in his 4th year because he was the most succesful student during his first 3 classes study at the faculty. He graduated from İzmir Atatürk High School in 1991.

Asst. Prof. Dr. ELMAS has completed his military service as a NATO Officer in Bosnia and Herzegovina. He was a “Reserved Officer” as a “2nd Lieutenant” as an “English-Turkish Interpreter”. He was also a “Guard Commander” and served in Sarajevo, Camp Butmir within the SFOR task force of NATO. He has been awarded with 2 (two) NATO Medals and Turkish Armed Forces Service Certificate of Pride (Bosnia & Herzegovina).

In addition to his academic duties at universities, he has worked as an engineer and manager in various industrial institutions, organizations and companies; He has served as Construction Site Manager, Project Manager, Management Representative, Quality Manager, Production

Manager, Energy Manager, CSO-CTO, CBDO, Factory Manager, Deputy General Manager and General Manager.

Asst. Prof. Dr. Elmas is Department Head and is an Assistant Professor of Automotive Technology at the Department of Motor Vehicles and Transportation Technologies at Vocational School of Higher Education for Technical Sciences at IGDIR UNIVERSITY, Turkey. He is also an Assistant Professor of Bioengineering & BioSciences at the same university. He has nearly 30 years of total experience in academia and in industry.

He has served as a scientific referee and panelist for ASME, TUBITAK and many scientific institutions, organizations and universities, including NASA.

“Mechanical Engineering, Energy Transfer, Thermodynamics, Fluid Mechanics, Heat Transfer, Higher Mathematics, Evaporation, Heat Pipes, Space Sciences, Automotive, Bioengineering, Medical Engineering Applications, Neuroengineering, Medical Technique” are his academic and scientific fields of study; “Heating-Ventilation Air Conditioning Applications, Pressure Vessels, Heat Exchangers, Energy Efficiency, Steam Boilers, Power Plants, Cogeneration, Water Purification, Water Treatment, Industrial Equipment and Machinery, Welding Manufacturing, Sheet Metal Forming, Machining” are his industrial experience fields.

Asst. Prof. Dr. Emin Taner ELMAS is also a musician, saz (baglama) virtuoso player and ney (Nay, Turkish Reed Flute) performer. He plays also cümbüş instrument and performs darbuka rhythm instrument. He has a YouTube Music Channel (Emin Taner ELMAS) which includes some of his sound recordings of him playing the saz-baglama and blowing the ney. He composed the poem written by the great poet Âşık Veysel ŞATIROĞLU under the name of “Raşit Bey” in memory of his father Judge (Hâkim) Raşit ELMAS as “Raşit Bey Türküsü”, wrote it down, notated and published it as an academic article and broadcasted this song on his own music channel. He wrote the poems entitled “Canım Babam” and “Geldim Babam” which he wrote also in memory of his father and published in an academic literature journal, and composed instrumental musics for these poems. He also composed an instrumental song called “Annem Annem Türküsü” and gave it to his mother, Lawyer Tuna ELMAS, as a gift on Mother’s Day, 11.05.2025. He also has a poem titled "Ney and Neyzen." He also wrote and presented a poem titled "Esra Kardeşim" to his sister, Esra ELMAS, an archaeologist and English teacher. He has published books including "Saz-Bağlama Tuning System Method" (“Saz- Bağlama Akort Sistemi Metodu”) and "Ney and Neyzen; Ney's Pitches, Frets, Sound Stages, Octaves, Structure, Performance, Ney Maintenance and Basic Music Theory" (Ney ve

Neyzen; Ney'de Perdeler, Ses Devreleri, Oktavlar, Yapısı, İcrası, Ney Bakımı ile Temel Musiki Nazariyatı). He continues his artistic studies by writing various articles, books, poetry, lyrics and also realizing musical composition and repertoire works.

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