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Introduction

In the context of the gravitational waves study, there are mainly two possible paths: the first is the **analysis of existing data** from experiments like Ligo, Virgo and Kagra, with the goal of detecting and characterizing the observable sources within their relative frequency bands; the second approach is the **forecasting approach**, which aims to characterize future experiments in order to better understand what types of sources they could detect and how well.

One of the most important future detectors is the European *Laser Interferometer Space Antenna* (LISA), the first space-based gravitational wave detector. LISA will be arranged as an equilateral triangle with 2.5 million kilometers long arms, placed in a heliocentric orbit, and will operate within the frequency range from approximately 0.1mHz to 1Hz. Among the typical sources that emit gravitational wave signal in this range are the **compact binaries**, and in our particular case we are interested in **double white dwarf binaries** (**WDBs**).

The goal of this work is to estimate the gravitational wave background produced by the extragalactic WDBs in the local universe, by using the **COSMIC** code to generate synthetic astrophysical populations to represent the galaxies listed in the **Gravitational Wave Galaxy Catalog** (**GWGC**).

In **Chapter 1** we will introduce the theoretical foundations of gravitational waves, derive the amplitude of the signal generated by a binary system, and define the most important parameters. Finally, we discuss how to combine the signals from multiple sources, to find a cumulative background.

In **Chapter 2** we will give a brief overview of how gravitational wave detectors work, trying to better understand what kinds of sources LISA will be able to see, what resolution and what sensitivity it will have and why in particular we are interested in WDBs.

In **Chapter 3** we introduce the concept of stellar population synthesis and the code COSMIC used for this purpose. We will introduce its features, main parameters, and pipeline, and explain how it is used to generate full-size astrophysical populations of WDBs.

In **Chapter 4** we introduce the GWGC, list the key information it provides and explain how we move from there to infer the remaining parameters that we need.

In **Chapter 5** we use the obtained information to compute the total gravitational wave signal summing the contribution from all the simulated sources, taking into account their spatial distribution, LISA's frequency resolution, and the *zone of avoidance* caused by the milky way.

In **Chapter 6** we plot the total resulting signal on the LISA sensitivity curve, and discuss the results and their possible implications.

Finally, in **Chapter 7** we will draw some conclusions from the work as a whole, discussing its limitations, assumptions and its possible extensions and follow-ups.

Chapter 1

Gravitational Waves Theory

After considering, in 1905, the problem of the apparently *instantaneous* propagation of light, with the theory of Special Relativity, in 1916 Albert Einstein considered the problem of the apparently *instantaneous* propagation of gravity through *long distances*, in his theory of General Relativity. Einstein showed that long-distance interaction arises from the deformation of spacetime caused by massive objects. Hence, in the "static case", the deviated motion apparently caused by the interaction between two distant masses really is, in fact, a manifestation of spacetime curvature nearby, generated by the presence of the two objects. The "static case" just depicted, though, treats the curvature as if it had always been there, and doesn't take into account of any variation in the masses, positions or velocities of the two objects, that would induce an evolution to the curvature itself. In truth, after a change in the mass-energy distribution, the corresponding curvature variation requires its time to reach far distances, and a fascinating prediction of General Relativity is that it propagates in the form of a wave, that travels at the speed of light.

1.1 Gravitational Waves as Perturbations

The tipical approach to the study of gravitational waves is to derive them as small perturbations of the background from the Einstein's equations:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R, \tag{1.1}$$

which can be conveniently written as

$$R_{\mu\nu} = \frac{8\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right), \tag{1.2}$$

where $G_{\mu\nu}$ is the Einstein tensor, $R_{\mu\nu}$ is the Ricci tensor, R is the Ricci scalar, $g_{\mu\nu}$ is the metric of spacetime, and $T_{\mu\nu}$ is the stress-energy tensor. As a background solution we can consider the flat spacetime described by the metric $\eta_{\mu\nu}$, to which the perturbation term appears as a fluctuation in the metric $|h_{\mu\nu}| \ll |\eta_{\mu\nu}|$, known as *weak field* approximation. Thus, the perturbed spacetime can be written as:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll |\eta_{\mu\nu}|.$$

With this metric, the equations 1.2 becomes

$$\{\Box_F h_{\mu\nu} - \left[\frac{\partial^2}{\partial x^\lambda \partial x^\mu} h^\lambda_\nu + \frac{\partial^2}{\partial x^\lambda \partial x^\nu} h^\lambda_\mu + \frac{\partial^2}{\partial x^\nu \partial x^\mu} h^\lambda_\lambda\right]\} = -\frac{16\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}T\right).$$

Now, by requiring that the *weak-field* approximation remains satisfied for infinitesimal diffeomorphisms, and by choosing a coordynate system in which the *harmonic gauge condition*[1] is satisfied, we can find that, up to first order in $h_{\mu\nu}$, the harmonic gauge condition is equivalent to

$$\frac{\partial}{\partial x^\mu} h^\mu_\rho = \frac{1}{2}\frac{\partial}{\partial x^\rho} h, \qquad h = \eta^{\mu\nu} h_{\mu\nu} \equiv h^\nu_\nu, \tag{1.3}$$

and after defining the tensor[2]

$$\bar{h}_{\mu\nu} \equiv h_{\nu\mu} - \frac{1}{2}\eta_{\mu\nu} h,$$

we can finally write the linearized Einstein equations as

$$\begin{cases} \Box\, \bar{h}_{\mu\nu} = -\dfrac{16\pi G}{c^4} T_{\mu\nu}, \\ \partial^\mu \bar{h}_{\mu\nu} = 0. \end{cases}$$

This form, and its twin with $T_{\mu\nu} = 0$, where the first equation becomes the D'Alambert equation, are relevant because they show that *a perturbation of a flat spacetime propagates as a wave travelling at the speed of light.*

[1]It is an arbitrary coordinate condition which makes it possible to solve the Einstein field equations. It can be found by requiring that the linearized Einstein equations satisfy the D'Alambert equation.

[2]Also known as *trace-reversed* perturbation tensor, since $\bar{h} = \eta^{\mu\nu}\bar{h}_{\mu\nu} = -h$.

1.1.1 Harmonic gauge

1.1.2 The TT gauge

1.2 Motion and geodesics

1.2.1 The motion deviation

1.2.2 The geodesic deviation

1.3 The Quadrupole Approximation

1.3.1 The weak-field, slow-motion approximation

1.3.2 The quadrupole formula

1.3.3 Transform to the TT gauge

1.4 Gravitational waves from a binary system

1.4.1 General solution for circular orbits

Up to 13.86/7 at page 255 of the book.

1.5 Energy carried by a gravitational wave

1.5.1 Stress-energy pseudo-tensor

1.5.2 Gravitational wave luminosity

1.6 Evolution of a compact binary system

1.6.1 Signal from inspiralling compact objects

Here we get to the actual amplitude we used, and the parameters involved.

1.6.2 ASD and multiple sources

Chapter 2

LISA

2.1 interferometers

- Instrument description (what is an interferometer, why in space, how it will be made, orbit) - frequency band - what will it see? - frequency resolution - sensibility curve and ASD meaning - Why WD choice in particular?

Chapter 3

COSMIC and Stellar Populations Synthesis

- COSMIC introduction (reference Breivik, BSE, general information) - COSMIC pipeline (why it's quick, intro to fixed population idea, match conditions, ...) - important parameters in COSMIC (the ones user chooses - stress on metallicity relevance) - population's parameters (the ones COSMIC gives to user) - parameter distribution graphs - Scaling to astrophysical population, what is needed (refer to next chapter

Chapter 4

GWGC and Galaxy Properies

- Catalog introduction and description (what it has - what we need) - How we'll get what we need (brief description of how we use catalog info to get what we want) - T value to Class - Class to Mass-Luminosity relation -> Mass (Faber & Gallagher) - Finding each galaxy's metallicity from the mass (Tremonti - Allende Prieto) - Metallicity bins for GWGC galaxies

Chapter 5

Total Gravitational Wave Signal

- For each galaxy: - Compute right N_astro - compute each binary's GW signal; - bin it to LISA's frequency sensibility bins - Plot it on LISA's sensibility curve - Zone of avoidance: how to consider all the sky

Chapter 6

Results

- Plot of spectral distribution of the computed signal - Analysis of the distribution of the sources - Eventual implications (none, since it shouldn't be visible)

Chapter 7

Conclusions and Future Perspectives

Recap of the whole Work - Limits of the Work, assumptions and approximations used - Possible extensions

Appendix A

Appendix

Dettagli tecnici sul codice.

Tabelle di parametri.

Ulteriori grafici.

Script di calcolo, se rilevante.

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