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Observation-guided Simulation of the Extragalactic Binary Gravitational Wave Foreground

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ANNO ACCADEMICO 2024/2025

Contents

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

The abundance of information of the electromagnetic spectrum allowed us to build highly detailed models of various celestial objects such as stars, both on their individual internal structure and on how this is influenced by the interaction with other bodies, for instance in binary systems. In the pursuit of reaching a greater sensitivity in the gravitational counterpart too, which could potentially reveal new information, or place better constrains on the existing models, these stellar models, when combined with a good theory of gravity, can be used to construct synthetic populations that reproduce observable features like luminosity, color, and chemical composition, which could enable us to predict what their gravitational signal would look like. In gravitational waves research, our observational capabilities are still very limited, and the signals are still comparatively very weak relative to their electromagnetic counterpart. Thererfore, methods that rely on simulations can be very useful both to explore how different sources could look like in the gravitational wave domain, and how effectively they could be detected with current or future instruments.

3.1 Stellar populations synthesis codes

Generating a synthetic population of stars is a very complex task, that involves multiple steps, each involving important choices. *First*, we need to choose a starting point: we could start from the very beginning of stars formation and simulate all the process from the birth onward, or we could select a later phase in the stars evolution, shared from the most, in order to reduce unnecessary computational power and time consumption. If we want to simulate entire stellar populations choosing a starting point also implies selecting appropriate distributions for the main parameters that characterize the "starting point population", like masses, metallicities, but also orbital parameters for the stars that are in binary systems, like orbital period, distance, and eccentricity. *Second*, we must choose how the stars will evolve from the starting point, and this involves the single star evolution but also the effects that interaction with other stars in binary systems have on it. *Finally*, we have to decide when we want to stop the simulation, choosing an endpoint that aligns with the needs of this study.

3.1.1 The starting point

As we know, in the Hertzsprung-Russel diagram, which plots the *luminosity* of the stars vs their *color index*, most of the stars appear distributed in the **main sequence** (**MS**), a continuous and distinctive band. A star's position on this band is determined by its initial mass, and a good rule of thumb is that the most massive stars are hotter, more luminous, and evolve more quickly, while the lower-mass stars burn their fuel more slowly, and remain on the MS longer.

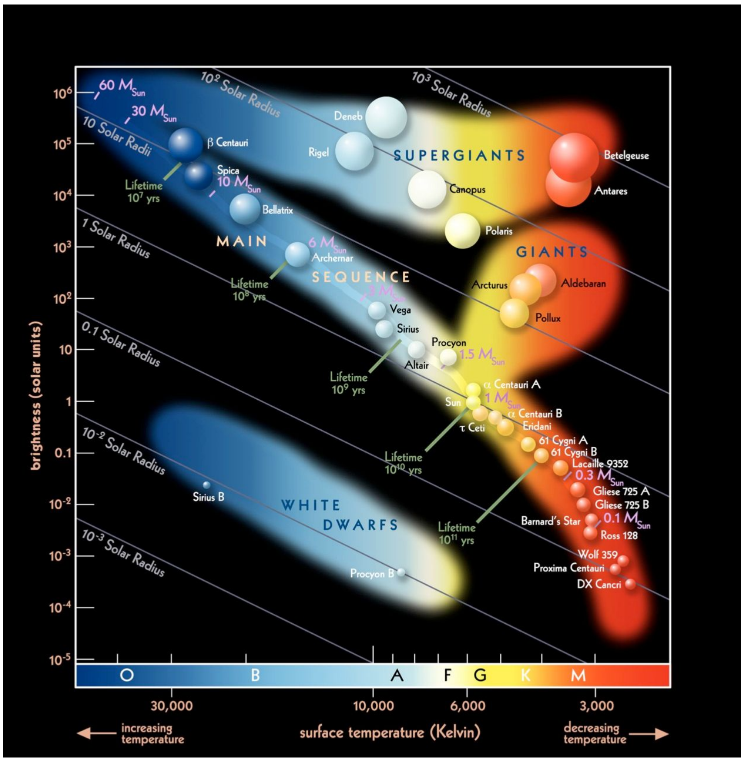

Figure 3.1: WRITE CAPTION, INSERT REFERENCE

Since almost all stars go through a phase in the MS, and evolve from there differently, in this work, the chosen starting point for stellar evolution is the Zero Age Main Sequence (ZAMS). At this stage, stars have just begun hydrogen burning in their cores, marking the start of their stable main sequence phase. This allows to bypass the early phases of star formation, which are much less relevant to the gravitational wave sources of interest, while still capturing the essential evolutionary processes that lead to the formation of compact objects.

3.1.2 Single star evolution

Simulating the evolution of a single star is in itself a very complex matter, and the only way to make it computationally feasible in the context of large-scale population synthesis is to approximate the evolution for a wide range of mass M and metallicity Z. In fact, detailed evolution codes can require substantial computational time even for the evolution of a single star, which is not practical when generating a full-scale astrophysical population containing millions of stars. Also, in order to make population synthesis statistically robust a large enough number of stars of a certain type must be evolved in order to overcome stochastic noise (in particular, the Poisson noise for n simulations of a particular type of star, implies an error that grows as $\sqrt{n}$). A winning strategy, adopted by several population synthesis frameworks, is to pre-generate a large grid of detailed stellar evolution models, and use them to derive a number of interpolation formulae as functions that approximate stellar properties as a function of age, mass and metallicity. In Hurley et al. [2000b] this method is implemented through the development of a set of **Single Star Evolution** (**SSE**) formulae, with the result of a very compact, efficient and adaptable code, which makes it perfect for the integration of binary-star interactions. The work presented in Hurley et al. [2000b] therefore serves as the theoretical and computational foundation for many complex stellar population synthesis codes, including the one used in this thesis. It takes care of the single-star evolution of stars from ZAMS through all the possible evolutionary outcomes, depending on the star's initial conditions.

3.1.3 Binary stars evolution

While the evolution of single stars already represents a challenge, the inclusion of binary interactions introduces a much higher level of complexity. In such systems, the evolution of each star is strongly influenced by its companion through a variety of processes, such as mass transfer and accretion, common envelope evolution, collisions, supernova kicks, tidal effects, angular momentum loss, and mergers. These interactions can drastically alter the final outcomes, and are essential for modeling the formation of compact binaries that are potential gravitational wave targets for LISA. To efficiently model binary evolution within the framework of stellar population synthesis, the work of Hurley et al. [2002b] extends the SSE formalism by introducing a set of prescriptions for binary interactions, and updating the treatment of processes such as Roche lobe overflow, common envelope evolution ans coalescence by collision, leading to the development of the **Binary Star Evolution** (**BSE**) algorithm. This code includes the interpolation-based approach used in SSE for single-star evolution, but adds a comprehensive treatment of binary-specific processes, enabling the simulation of a wide range of binary configurations but keeping the affordable computational requirements of SSE. The BSE algorithm tracks the joint evolution of both stars in a binary system, taking into account their initial parameters, such as masses, orbital period, eccentricity, and metallicity, and updates these properties dynamically as the system evolves. The flexibility and speed of the

BSE code make it a key component in many modern population synthesis tools, including the one used in this thesis, which we will now introduce.

3.2 COSMIC

For the purposes of this work, we employ a community-developed binary population synthesis (BPS) python-based code, called the **Compact Object Synthesis and Monte Carlo Investigation Code** (**COSMIC**), whose «*primary purpose is to generate synthetic populations with an adaptive size based on how the shape of binary parameter distributions change as the number of simulated binaries increases*» [1]. COSMIC's binary evolution is built upon BSE, incorporating extensive modifications in order to include updated physical prescriptions. It includes all necessary tools to generate a population, from the generation of initial conditions, to scaling the simulated systems to full-scale astrophysical populations. The code is presented in Breivik et al. [2020], where it is described in full detail and used, as a proof of concept, to simulate the Galactic population of compact binaries and their associated gravitational wave signal. In the following section we will see the main features of the code, and explain what makes it the right choice for this thesis work.

3.2.1 Fixed population

A fundamental concept in COSMIC, which is the key to the code's efficiency, is the idea of *fixed population*. This refers to a relatively small sample[2] of just enough binaries to capture, in a statistically meaningful way, the underlying shape of the parameter distribution functions of the target population, as determined by the user specified Star Formation History (SFH) and evolution model. This is achieved following an iterative process designed to reach a convergence with respect to a defined matching condition, and consists of five key steps:

1. The user selects a binary evolution model and SFH;

2. Based on the SFH and the chosen initial parameter distribution, an initial population is generated;

3. The population evolves for a user specified number of steps, according to the selected evolution model;

4. If it is the first iteration, half of the simulated systems is compared with the total population. In the following steps, the population from the previous one gets compared to the population containing both the current and previous

[1] `https://cosmic-popsynth.github.io/docs/stable/pages/about.html`

[2] Note that, from now on, every time we talk about sampling, that is where the "M" of COSMIC comes into play: this code uses proficiently the Monte Carlo Markov Chain methods to sample populations and parameter distributions, as will follow in this section.

iterations. In any case, the comparison is done in order to check if the matching condition has been achieved;

5. Once the parameter distributions of the population have converged, the corresponding population is called *fixed population*, which represents the statistical features of a binary evolution model.

In practice, the fixed population is the converged, computationally efficient representation of the systems that we want to simulate, embedded in a complete small-scale synthetic galaxy that also contains other stellar components. The output is stored in a data frame, which separates the full galaxy properties from the fixed population ones. The last step required to construct a full size galaxy is to scale the fixed population (by mass or by number of stars) with a re-sampling approach with replacement, allowing to extrapolate a larger final population that preserves the statistical properties encoded in the fixed population.

Initialization

The fixed population is generated from an initial collection of binaries sampled from distribution functions to assign to each binary an initial value of metallicity (Z), primary star mass (m), mass ratio (q), orbital separation (a), eccentricity (e), and birth time (T_0) according to the selected SFH. In COSMIC the user can choose between different binary parameter distributions, and different parameters can be treated independently. Moreover, COSMIC allows a complete personalization of the initial population through a number of other parameters, including different timesteps to control the binary physics, metallicity, stellar winds, common envelope phase, natal kicks, remnant mass, remnant spin, gravitational wave orbital decay, mass transfer, tides, and particular specifications for different kinds of stellar objects, mixing variables, and magnetic braking. In this work all the parameters were left default, but one: we tweaked the metallicity value, in order to differentiate fixed populations describing the parameter distributions for galaxies of different types. We will go more into detail on this topic in the next chapters.

Convergence

The number of simulated systems in the fixed population ideally describes the final parameter distribution functions while being low enough to keep the code efficient. Since every population depends on a different binary evolution model, to quantify this number a *discrete match criteria* is developed, based on the work Chatziioannou et al. [2017]. Independently generated histograms for each parameter are used to track their distribution as successive populations are generated and cumulatively added to the fixed population. The physical limits of the simulated systems are then enforced by taking the logistic transform, and finally the match is defined as:

$$match = \frac{\sum_{k=1}^{N} P_{k,i}P_{k,i+1}}{\sqrt{\sum_{k=1}^{N}(P_{k,i}P_{k,i})\sum_{k=1}^{N}(P_{k,i}P_{k,i+1})}},$$

where $P_{k,i}$ is the probability for the kth bin, for the ith iteration. For how it is defined, the match value shifts between 0 and 1, and tends to unity as the parameter distributions converge to a distinct shape.

3.2.2 The output

Since COSMIC uses BSE as it's core binary evolution algorithm, the output of COSMIC follows most of the same conventions as BSE. The *kstar values* (e.g. the number that represent a specific stellar type) and evolution stages are nearly identical to their BSE counterparts, and the exact references can be found in the **Appendix**. In order to generate a fixed population, the COSMIC can be ran through a one-line command directly on the terminal, specifying a parameter file, the kstar values for the primary and secondary star, the maximum number of systems to evolve, every how many systems to check in, in order to track the distributions of the parameters, and how many processors to use. The final output is in an *hdf5* file containing several data frames, that keep track pf various important quantities during the evolution: the total number of stars and total mass of the entire population, the number of binaries, the convergence, and so on. The *conv* data frame contains all the information about the final fixed population, and thus is the one that we will use the most: from it we can extract all the parameter distributions of the fixed population, such as the orbital parameters, and the individual star information. The parameter distributions of a fixed population of binary white dwarfs with a default metallicity value set at 0.020 is shown in **Figure 3.2**.

3.3 Astrophysical population

Once the convergence criteria is achieved, an astrophysical population can be sampled. The number of sources in the astrophysical population $N_{astro,tot}$ can be found by upscaling the size of the fixed population, N_{fixed} ,by the ratio of the mass of the astrophysical population, M_{astro}, to the mass of all the stars in the whole small-scale galaxy in which the fixed population is embedded, $M_{fixed,stars}$, as follows:

$$N_{astro} = N_{fixed}\frac{M_{astro,tot}}{M_{fixed,stars}}, \tag{3.1}$$

or by the ratio of the number of stars in the astrophysical population, $N_{astro,tot}$, to the total number of stars formed to produce the fixed population, $N_{fixed,tot}$,

$$N_{astro} = N_{fixed}\frac{N_{astro,tot}}{N_{fixed,stars}}. \tag{3.2}$$

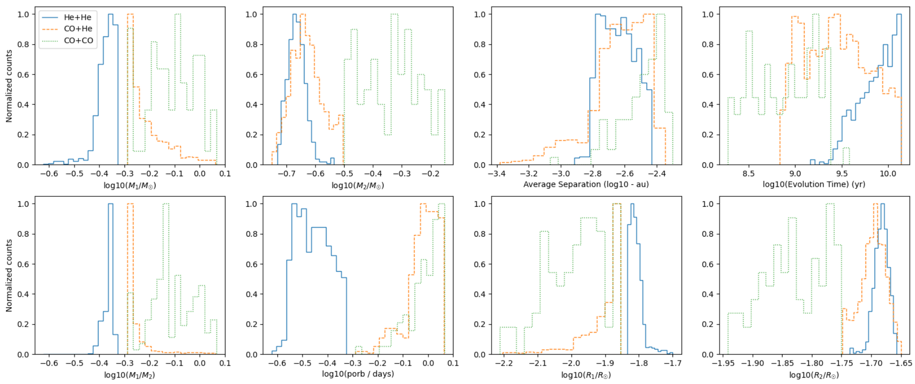

Figure 3.2: Distributions of the parameters of a fixed population with metallicity $Z = 0.020$ composed of He+He, CO+He and CO+CO binary white dwarfs. This includes the mass, radius of primary and secondary stars, the radius ratios between the two, the orbital period, average separation, and evolution time.

Thus, to create a full-scale astrophysical population we need a reference population from which we can extract either the total mass or the total number of stars, to then use to scale up our fixed population. As will follow in **Chapter 4**, we will use a catalog which reports the total mass of the galaxies in it, so we will proceed using the method in (3.1).

Chapter 4

GWGC and Galaxy Properies

As we have seen in **Chapter 2**, the goal of this work is to simulate the gravitational wave background produced by compact binaries in the local universe. To do this, we must first generate the populations emitting this signal, and we do this by using COSMIC to replicate the existing, observed galaxies in the vicinity of the Milky Way and simulate their stellar content. To access the required galactic properties, we rely on the dataset provided in White et al. [2011], the **Gravitational Wave Galaxy Catalog** (**GWGC**). This catalog includes a list of $53,255$ galaxies within $100Mpc$ from earth, containing information on sky position, distance, blue magnitude, major and minor diameters, position angle, and galaxy type, currently used for follow-up searches of electromagnetic counterparts from gravitational wave searches.

4.1 What it has vs what we need

In principle, we could generate a separate fixed population for each galaxy in the GWGC and scale it individually. However, this is simply not practical because of the computational power and time it would require, and therefore we must find a strategy to group them in a few, representative, categories. As we will show in this section, many of the information in the GWGC can be used to infer the missing astrophysical quantities we need for population synthesis. Ultimately, we will find that metallicity is the most suitable parameter for grouping galaxies. To get there, we follow a chain of empirical relations, starting from the galaxy morphological type, through a luminosity to mass, and then a mass to metallicity relation. This process will enable us to provide COSMIC with the necessary input, found in a consistent and astrophisically motivated way.

4.1.1 Galaxy types

- T value to Class

4.1.2 Mass-luminosity relation

- Class to Mass-Luminosity relation -> Mass (Faber & Gallagher)

4.1.3 Mass-metallicity relation

- Finding each galaxy's metallicity from the mass (Tremonti - Allende Prieto)

4.2 The final fixed populations

4.2.1 Final catalog editing

- Graphs of catalog distributions

4.2.2 Metallicity categorization

- Metallicity bins for GWGC galaxies, and corresponding fixed populations

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.

INSERISCI TABELLE COI KSTAR VALUES ETC

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