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GW Notes was born from the need for a journal where the distinct communites involved in gravitation wave research might gather. While these three communities - Astrophysics, General Relativity and Data Analysis - have made significant collaborative progress over recent years, we believe that it is indispensible to future advancement that they draw closer, and that they speak a common idiom.

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Intention and purpose of GW Notes

The electronic publishing service **arXiv** is a dynamic, well-respected source of news of recent work and is updated daily. But, perhaps due to the large volume of new work submitted, it is probable that a member of our community might easily overlook relevant material. This new e-journal and its blog, **The LISA Brownbag**, both produced by the AEI, propose to offer scientist of the Gravitational Wave community the opportunity to more easily follow advances in the three areas mentioned: Astrophysics, General Relativity and Data Analysis. We hope to achieve this by selecting the most significant e-prints and publish them in abstract form with a link to the full paper in both a single e-journal (GW Newsletter) and a blog (The LISA Brownbag). Of course, *this also implies that the paper will have its impact increased, since it will reach a broader public*, so that we encourage you to not forget submitting your own work

In addition to the abstracts, in each PDF issue of GW Notes, we will offer you a previously unpublished article written by a senior researcher in one of these three domains, which addresses the interests of all readers.

Thus the aim of The LISA Brownbag and GW Notes is twofold:

- Whenever you see an interesting paper on GWs science and LISA, you can submit the **arXiv** number to our **submission page**. This is straightforward: No registration is required (although recommended) to simply type in the number in the entry field of the page, indicate some keywords and that's it

- We will publish a new full article in each issue, if available. This "feature article" will be from the fields of Astrophysics, General Relativity or the Data Analysis of gravitational waves and LISA. We will prepare a more detailed guide for authors, but for now would like to simply remind submitters that they are writing for colleagues in closely related but not identical fields, and that cross-fertilization and collaboration is an important goal of our concept

GW Notes is also timely, since it will help crystallise people's thoughts on issues of importance, when reading some of the documents for presentation to the **Astro2010** that set the priority list for the the astronomy and astrophysics decadal survey.

Subscribers will get the issue distributed in PDF form. Additionally, they will be able to submit special announcements, such as meetings, workshops and jobs openings, to the list of registered people.

This first issue is an exception. If you want to get the forthcoming numbers of GW Notes, please register at the **registration page** by filling in your e-mail address and choosing a password.

Philosophy behind: The Astro-GR meetings

Sixty two scientists attended the **Astro-GR@AEI** meeting, which took place September 18-22 2006 at the **Max-Planck Institut für Gravitationsphysik (Albert Einstein-Institut)** in Golm, Germany. The meeting was the brainchild of an AEI postdoc, who had the vision of bringing together Astrophysicists and experts in General Relativity and gravitational-wave Data Analysis to discuss sources for **LISA**, the planned Laser Interferometer Space Antenna. More specifically, the main topics were EMRIs and IMRIs (Extreme and Intermediate Mass-Ratio Inspiral events), i.e. captures of stellar-mass compact objects by supermassive black holes and coalescence of intermediate-mass black holes with supermassive black holes.

The format of the meeting was that roughly two-thirds of the meeting was devoted to talks -broad, review talks for the first two days of the meeting and more specific talks on recent work in the latter half-, while the remaining third was given to group discussion of questions that participants agreed to be especially vital.

The general consensus was that the meeting was both interesting and quite stimulating. It was generally agreed that someone should step up and host a second round of this meeting. Monica Colpi kindly did so and this led to **Astro-GR@Como**, which was very similar in its informal format, though with a focus on all sources, meant to trigger new ideas, as a kind of brainstroming meeting.

Also, in the same year, in the two first weeks of September, we had another workshop in the Astro-GR series with a new "flavour", namely, the **Two Weeks At The AEI (2W@AEI)**, in which the interaction between the attendees was be even higher than what was reached in the previous meetings. To this end, we reduced the number of talks, allowing participants more opportunity to collaborate. Moreover, participants got office facilities and we combined the regular talks with the so-called "powerpointless" seminar, which will were totally informal and open-ended, on a blackboard.

The next one will be held in Barcelona in 2009 at the beginning of September:

LISA Astro-GR@BCN (Barcelona, Monday 7th to Friday, September 11th 2009)

Pau Amaro-Seoane, Priscilla Cañizares, Carlos F. Sopuerta and Alberto Lobo will organise it and it will be held at the ICE (CSIC-IEEC) in Barcelona from Monday 7th to Friday, September 11th 2009

After that, the next one will be in Zurich in 2010, as Phillippe Jetzer announced at the end of the Como meeting.

A proper Astro-GR meeting must closely follow the *Five Golden Rules*:

- I. Bring together Astrophysicists, Cosmologists, Relativists and Data Analysts
- II. Motivate new collaborations and projects
- III. Be run in the style of Aspen, ITP, Newton Institute and Modest meetings, with plenty of time for discussions
- IIII. Grant access to the slides in a cross-platform format, such as PDF and, within reason, to the recorded movies of the talks in a free format which everybody can play like **Theora**, for those who could not attend, following the good principles of **Open Access**
- IIIII. Keep It Simple and... Spontaneous

This is how the series of meetings "Astro-GR" and its new *flavour*, the 2W@AEI, inspired us to create this e-journal. Of course, we have also been encouraged by the excellent pioneer e-journals **GCNews**, a newsletter for Galactic centre research and **SCYON**, the "Star Clusters Young & Old Newsletter" which are enjoying a very favorable reception.

We believe that GW Notes will fill a definite void.

Pau Amaro-Seoane & Bernard F. Schutz, editors

GW Notes highlight article: Astrophysics

BINARY SOURCES OF GRAVITATIONAL RADIATION

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Abstract

The only sources of gravitational waves that are absolutely secure are binaries. Fortunately, this still allows us wide scope in the nature of the binaries and what we will learn from them, from tests of strong gravity to populations of stellar-mass black holes to hierarchical merging of supermassive black holes. Here we give a general overview of the properties of gravitational radiation from binaries, including some recent results from numerical relativity.

1 Introduction

Of all the proposed sources of gravitational radiation, binaries are the most reliable because we actually can observe binary neutron stars with orbits that decay just as predicted. The characteristics of the gravitational waves from binaries, and what we could learn from them, depend on the nature of the objects in those binaries. We therefore begin with some general concepts and then discuss individual types of binaries.

2 Available frequencies

For a given type of binary, what is the possible range of frequencies? There is obviously no practical lower frequency limit (just increase the semimajor axis as much as desired), but there is a strict upper limit. The two objects in the binary clearly will not produce a signal higher than the frequency at which they are in contact. If we consider an object of mass M and radius R, the orbital frequency at its surface is $\sim \sqrt{GM/R^3}$. Noting that $M/R^3 \sim \rho$, the density, we can say that the maximum frequency involving an object of density ρ is $f_{\rm max} \sim (G\rho)^{1/2}$. This is actually more general than just orbital frequencies. For example, a gravitationally bound object cannot rotate faster than this frequency, because it would fly apart. In addition, you can convince yourself that the frequency of a sound wave through the object cannot be greater than $\sim (G\rho)^{1/2}$. Therefore, this is a general upper bound on dynamical frequencies.

This tells us that binaries involving main sequence stars cannot have frequencies greater than $\sim 10^{-3} - 10^{-6}$ Hz, depending on mass (lower-mass stars are denser and thus have higher maximum frequencies), that binaries involving white dwarfs can't have frequencies greater than ~ 0.1–10 Hz, also depending on mass, that for neutron stars the upper limit is $\sim 1000 - 2000$ Hz, and that for black holes the limit depends inversely on mass (and also spin and orientation of the binary). In particular, for black holes the maximum imaginable frequency is on the order of $10^4(M_\odot/M)$ Hz at the event horizon, but in reality the orbit becomes unstable at somewhat lower frequencies (more on that later).

Now suppose that the binary is well-separated, so that the components can be treated as points and we only need take the lowest order contributions to gravitational radiation. Temporarily restricting our attention to circular binaries, how will their frequency and amplitude evolve with time?

3 Quadrupolar evolution of circular orbits

Let the masses be m_1 and m_2, and the orbital separation be R. The amplitude a distance $r \gg R$ from this source is $h \sim (\mu/r)(M/R)$, where $M \equiv m_1 + m_2$ is the total mass and $\mu \equiv m_1 m_2/M$ is the reduced mass. We can rewrite the amplitude using $f \sim (M/R^3)^{1/2}$, to read

$$\begin{aligned} h &\sim \mu M^{2/3} f^{2/3}/r \\ &\sim M_{ch}^{5/3} f^{2/3}/r \end{aligned}$$

where M_{ch} is the "chirp mass", defined by $M_{ch}^{5/3} = \mu M^{2/3}$. The chirp mass is thus named because it is this combination of μ and M that determines how fast the binary sweeps, or chirps, through a frequency band. When the constants are put in, the direction-averaged dimensionless gravitational wave strain amplitude (i.e., the fractional amount by which a separation changes as a wave goes by) measured a distance r from a circular binary of masses M and m with a binary orbital frequency $f_{\rm bin}$ is (Schutz, 1997)

$$h = 2(4\pi)^{1/3}\frac{G^{5/3}}{c^4} f_{\rm GW}^{2/3} M_{ch}^{5/3}\frac{1}{r}\,, \tag{1}$$

where $f_{\rm GW}$ is the gravitational wave frequency. Redshifts have not been included in this formula.

The luminosity in gravitational radiation is then

$$\begin{aligned} L &\sim 4\pi r^2 f^2 h^2 \\ &\sim M_{ch}^{10/3} f^{10/3} \\ &\sim \mu^2 M^3/R^5 \end{aligned}$$

The total energy of a circular binary of radius R is $E_{\rm tot} = -G\mu M/(2R)$, so we have

$$\begin{aligned} dE/dt &\sim \mu^2 M^3/R^5 \\ \mu M/(2R^2)(dR/dt) &\sim \mu^2 M^3/R^5 \\ dR/dt &\sim \mu M^2/R^3 \end{aligned}$$

What if the binary orbit is eccentric? The formulae are then more complicated, because one must then average properly over the orbit. This was done first to lowest order by Peters et Mathews, 1963 and Peters, 1964, by calculating the energy and angular momentum radiated at lowest (quadrupolar) order, and determining the change in orbital elements that would occur if the binary completed a full Keplerian ellipse in its orbit. That is, they assumed that to lowest order, the binary moves as if it experiences only Newtonian gravity. They then integrated the energy and angular momentum losses along that path.

Before quoting the results, we can understand one qualitative aspect of the radiation when the orbits are elliptical. From our derivation for circular orbits, we see that the radiation is emitted much more strongly when the separation is small, because $L \sim R^{-5}$. Consider what this would mean for a very eccentric orbit $(1-e) \ll 1$. Most of the radiation would be emitted at pericenter, hence this would have the character of an impulsive force. With such a force, the orbit will return to where the impulse was imparted. That means that the pericenter distance would remain roughly constant, while the energy losses decreased the apocenter distance. As a consequence, the eccentricity decreases. Gravitational radiation usually decreases the eccentricity of an orbit, although near the innermost stable circular orbit (ISCO) this is not necessarily true..

The Peters formulae bear this out. If the orbit has semimajor axis a and eccentricity e, their lowest-order rates of change are

$$\langle \frac{da}{dt} \rangle = -\frac{64}{5} \frac{G^3 \mu M^2}{c^5 a^3 (1-e^2)^{7/2}} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) \tag{2}$$

and

$$\langle \frac{de}{dt} \rangle = -\frac{304}{15} e \frac{G^3 \mu M^2}{c^5 a^4 (1-e^2)^{5/2}} \left(1 + \frac{121}{304}e^2\right) \tag{3}$$

where the angle brackets indicate an average over an orbit. One can show that these rates imply that the quantity

$$a e^{-12/19} (1-e^2) \left(1 + \frac{121}{304}e^2\right)^{-870/2299} \tag{4}$$

is constant throughout the inspiral.

Evidence that these formulae actually work comes from observations of binary neutron stars. Several such systems are known, all of which have binary separations orders of magnitude greater than the size of a neutron star, so the lowest order formulae should work. Indeed, the da/dt predictions have been verified to better than 0.1% in a few cases. In contrast, the de/dt predictions will be much tougher to verify. The reason for the difference is that de/dt has to be measured by determining the eccentricity orbit by orbit, whereas da/dt has a manifestation in the total phase of the binary, hence it accumulates quadratically with time. These systems provide spectacular verification of general relativity in weak gravity. In particular, in late 2003 a double pulsar system was detected, that in addition has the shortest expected time to merger of any known system (only about 80 million years). Having two pulsars means that extra quantities can be measured (such as the relative motion, which gives us the mass ratio), and in fact the system is now dramatically overconstrained (more quantities are measured than there are parameters in the theory). The tests of GR by observations of binary neutron star systems deservedly resulted in the 1993 Nobel Prize in physics going to Hulse and Taylor, who discovered the first such binary.

We are therefore quite confident that, at least in weak gravity, gravitational radiation exists as advertised. What happens in strong gravity?

4 Binary evolution in strong gravity

When two masses are close enough to each other, the Peters formulae do not quite describe their motion. Instead, there are additional terms corresponding to higher order moments of the mass and current distributions: the octupole, hexadecapole, and so on. This is often expressed in terms of equations of motion that include the Newtonian acceleration and a series of “post-Newtonian" (PN) terms. The order of a term is labeled by the number of factors of M/r by which it differs from Newtonian: for example, the 1PN term is proportional to M/r times the Newtonian acceleration. Since $v^2 \sim M/r$ in a binary orbit, there can also be half-power terms. The first several corrections are at the 1PN, 2PN, 2.5PN (this is where gravitational radiation losses first enter), 3PN, and 3.5 PN orders.

The equations of motion have been fully, rigorously established up to 3PN order, but the algebra is daunting and serious technical challenges exist that make it difficult to determine unambiguously the coefficients in each succeeding set of terms. We note that, fortunately, tidal effects only enter at the 5PN order, which one can justify by realizing that tidal couples have a $1/r^6$ energy dependence, or five powers of r greater than the Newtonian potential. Therefore, for many purposes, tidal effects can be neglected. The post-Newtonian approach is useful, but problematic because succeeding terms are not much smaller than the terms before them. Another way to put this is that the Newtonian acceleration is overwhelmingly dominant for an extremely wide range of separations (out to infinity, in fact), but the range in which the 1PN term is necessary but the 2PN term is negligible is small, and this becomes even more true for the higher order terms. One can therefore often make good progress by taking the lowest-order term, and since the 2.5PN term is the lowest-order that involves energy and angular momentum loss, one can use the Newtonian plus 2.5PN terms. However, more terms turn out to be necessary to get sufficiently accurate waveforms for analysis of future gravitational wave data streams.

Various clever attempts have been made to recast the expansions into forms that converge faster than Taylor series. For example, a path adopted by Damour and Buonanno is to pursue equivalent one-body spacetimes in which an effective test particle moves, and to then graft on the effects of gravitational radiation losses. They also use Padé resummation, in which the terms are ratios of polynomials, in the hopes that this can more naturally model the singularity of black hole spacetimes.

5 Merger and ringdown

Generically, if two black holes coalesce, how does it happen? It is standard to divide the whole process up into three stages. The first stage is inspiral, which follows the binary from large separations to when the binary has reached the stage of dynamical instability. That is, inspiral is roughly where the binary is outside the innermost stable circular orbit, so the motion is mostly azimuthal. Inside the ISCO, the motion becomes a plunge, and this happens on a dynamical time scale. As the event horizons disturb each other and finally overlap, the spacetime becomes extremely complicated and must be treated numerically. This is called the merger phase.

Ultimately, of course, the “no hair" theorem guarantees that the system must settle into a Kerr spacetime. It does this by radiating away its bumpiness as a set of quasi-normal modes. The lowest-order, and longest-lived, of the modes is the $l = 2$, $m = 2$ mode. When all but this mode have essentially died away, the system has entered the period of ringdown. With only a single mode left, the ringdown phase can be treated numerically. The result is that the frequency f_{qnr} of the gravitational radiation, as well as the quality factor $Q \equiv \pi f_{qnr} \tau$ (where τ is the characteristic duration of the mode; this measures how many cycles the ringing lasts) depend on the effective spin $j \equiv cJ/GM^2$ of the final black hole (sometimes $\hat{a}$ is used instead of j). Echeverria, 1989 gives fitting formulae valid to $\sim 5\%$:

$$\begin{aligned} f_{qnr} &\approx [1 - 0.63(1 - j)^{0.3}](2\pi M)^{-1} \\ Q &\approx 2(1 - j)^{-0.45} \end{aligned}$$

Thus more rapidly spinning remnants have higher frequencies and last for more cycles. This could allow identification of the spin based on the character of the ringdown.

We can make rough estimates of the energy released in each phase as a function of the reduced mass μ and total mass M of the system. Since the inspiral phase goes from infinity to the ISCO, the energy released is simply μ times the specific binding energy at the ISCO, so $E_{\rm inspiral} \sim \mu$. What about the merger and ringdown phases? We know that the strain amplitude is $h \sim (\mu/r)(M/R)$, where r is the distance to the observer and R is the dimension of the system. For the merger and ringdown phases, $R \sim M$, so $h \sim \mu/r$. We also know that the luminosity is $L \sim r^2h^2f^2$, so $L \sim \mu^2 f^2$, and if the phase lasts a time τ then the total energy released is $E \sim \mu^2 f^2\tau$. But the characteristic frequency is $f \sim 1/M$ and the characteristic time is $\tau \sim M$, so we have finally $E \sim \mu^2/M$, or a factor $\sim \mu/M$ times the energy released in the inspiral. The exact values for a particular mass ratio are somewhat in dispute, but for an equal-mass nonspinning black hole binary, $E_{\rm inspiral} \sim 0.06M$ and $E_{\rm merger}$ and $E_{\rm ringdown}$ are probably $\sim 0.01M$. Note that for highly unequal mass binaries ($\mu \ll M$), the inspiral produces much greater total energy than the merger or ringdown. This is one reason why analyses of extreme mass ratio inspirals have ignored the merger and ringdown phases.

6 Gravitational radiation recoil

One interesting effect that emerges from the higher-order studies of binary inspirals is that gravitational radiation carries away net linear momentum, hence the center of mass of the system moves in an ever-widening spiral. We can understand this as follows (following a heuristic idea of Alan Wiseman). In an unequal-mass binary, the lower-mass object moves faster. As the speed in orbit becomes relativistic, the gravitational radiation from each object becomes beamed, with the lower-mass object producing more beaming because it moves faster. Note that this cheats a bit: the wavelengths are larger than the system itself, meaning that one can't assign radiation to one object or the other. However, this picture does give the correct answer that at any given instant, there is a net kick against the direction of motion of the lower-mass object. If the binary were forced to move in a perfect circle, the center of mass of the system would simply go in a circle as well. However, because in reality the orbit is a tight and diminishing spiral, the recoil becomes stronger with time and the center of mass moves in an expanding spiral. Note that by symmetry, equal-mass nonspinning black holes can never produce a linear momentum kick, and that if the mass ratio is gigantic the fractional energy release is small and therefore so is the kick. For nonspinning holes, the optimal ratio for a kick is about 2.6.

This process is potentially important astrophysically because if the final merged remnant of a black hole inspiral moves rapidly, it could be kicked out of its host stellar system, with possibly interesting implications for supermassive black holes and hierarchical merging. There have therefore been a number of calculations of the expected kick. It has turned out that these are very challenging. The primary reason is that most of the action is near the end, when the black holes are close to each other and simple approximations to the orbit are inaccurate. Analytic calculations (e.g., Peres, 1962, Bekenstein, 1973, Fitchett, 1983, Fitchett et Detweiler, 1984, Redmount et Rees, 1989, Wiseman, 1992, Favata et al., 2004, Blanchet et al., 2005, Damour et

Gopakumar, 2006, Schnittman et Buonanno, 2007, Boyle et Kesden, 2008, Boyle et al., 2008, Schnittman et al., 2008 et Racine et al., 2008), suggest that the kick due to inspiral from infinity to the ISCO is minimal, but that the final plunge could produce interesting speeds. In the last few years there has been tremendous progress in numerical relativity, and at this stage one can say that the kick can be estimated with good accuracy for any orientation, mass ratio, and spin magnitude (for calculations see Herrmann et al., 2007a, 2007b, Baker et al., 2006, 2007, 2008, Koppitz et al., 2007, Campanelli et al., 2007a, 2007b, González et al., 2007b, 2007a et Lousto et Zlochower, 2008a, 2008b). Remarkably, for spin axes in the orbital plane, one can end up with kicks of nearly 4000 km s^{-1}. This is larger than the escape speed from any galaxy. A Maryland collaboration (Bogdanović et al., 2007) suggests that in mergers of gas-rich galaxies, torques from the gas can align the spins with each other and with the orbital axis. If so, this reduces kicks to below 200 km s^{-1} and means that the remnant stays in any moderately large galaxy.

7 Summary

In conclusion, the gravitational radiation community eagerly awaits the detection of gravitational waves from binaries, because these will give us information about the total mass and mass ratio distributions of the binaries, their spins and orientations, and whether strong gravity works as we think it does. The role of kicks is likely to be very important when the systems have low escape speeds or when there is insufficient gas to align the holes (e.g., in mergers between two gas-poor galaxies). We can also hope for future observations that have electromagnetic counterparts, e.g., if some short hard gamma-ray bursts are produced by the mergers of two neutron stars, gravitational waves from the event will establish their nature. It is a bright field, and there are undoubtedly many analytical, numerical, and observational developments to come.

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Selected abstracts

Physics, Astrophysics and Cosmology with Gravitational Waves

Authors: Sathyaprakash, B. S.; Schutz, Bernard F.

Eprint: http://arxiv.org/abs/0903.0338

Keywords: Gravitational waves, Gravitational wave sources, Gravitational wave detectors, Data analysis

Abstract:

Gravitational wave detectors are already operating at interesting sensitivity levels, and they have an upgrade path that should result in secure detections by 2014. We review the physics of gravitational waves, how they interact with detectors (bars and interferometers), and how these detectors operate. We study the most likely sources of gravitational waves and review the data analysis methods that are used to extract their signals from detector noise. Then we consider the consequences of gravitational wave detections and observations for physics, astrophysics, and cosmology.

Gravitational waves from merging compact binaries

Authors: Hughes, Scott A.

Eprint: http://xxx.lanl.gov/abs/0903.4877

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics, General Relativity and Quantum Cosmology

Abstract:

Largely motivated by the development of highly sensitive gravitational-wave detectors, our understanding of merging compact binaries and the gravitational waves they generate has improved dramatically in recent years. Breakthroughs in numerical relativity now allow us to model the coalescence of two black holes with no approximations or simplifications. There has also been outstanding progress in our analytical understanding of binaries. We review these developments, examining merging binaries using black hole perturbation theory, post-Newtonian expansions, and direct numerical integration of the field equations. We summarize these approaches and what they have taught us about gravitational waves from compact binaries. We place these results in the context of gravitational-wave generating systems, analyzing the impact gravitational wave emission has on their sources, as well as what we can learn about them from direct gravitational-wave measurements.

Cosmic Swarms: A search for Supermassive Black Holes in the LISA data stream with a Hybrid Evolutionary Algorithm

Authors: Gair, Jonathan R.; Porter, Edward K.

Eprint: http://xxx.lanl.gov/abs/0903.3733

Keywords: General Relativity and Quantum Cosmology

Abstract:

We describe a hybrid evolutionary algorithm that can simultaneously search for multiple supermassive black hole binary (SMBHB) inspirals in LISA data. The algorithm mixes evolutionary computation, Metropolis-Hastings methods and Nested Sampling. The inspiral of SMBHBs presents an interesting problem for gravitational wave data analysis since, due to the LISA response function, the sources have a bimodal sky solution. We show here that it is possible not only to detect multiple SMBHBs in the data stream, but also to investigate simultaneously all the various modes of the global solution. In all cases, the algorithm returns parameter determinations within 5σ (as estimated from the Fisher Matrix) of the true answer, for both the actual and antipodal sky solutions.

Linear perturbations of black holes: stability, quasi-normal modes and tails

Authors: Zhidenko, Alexander

Eprint: http://xxx.lanl.gov/abs/0903.3555

Keywords: General Relativity and Quantum Cosmology

Abstract:

Black holes have their proper oscillations, which are called the quasi-normal modes. The proper oscillations of astrophysical black holes can be observed in the nearest future with the help of gravitational wave detectors. Quasi-normal modes are also very important in the context of testing of the stability of black objects, the anti-de

Sitter/Conformal Field Theory (AdS/CFT) correspondence and in higher dimensional theories, such as the brane-world scenarios and string theory. This dissertation reviews a number of works, which provide a thorough study of the quasi-normal spectrum of a wide class of black holes in four and higher dimensions for fields of various spin and gravitational perturbations. We have studied numerically the dependance of the quasi-normal modes on a number of factors, such as the presence of the cosmological constant, the Gauss-Bonnet parameter or the aether in the space-time, the dependance of the spectrum on parameters of the black hole and fields under consideration. By the analysis of the quasi-normal spectrum, we have studied the stability of higher dimensional Reissner-Nordstrom-de Sitter black holes, Kaluza-Klein black holes with squashed horizons, Gauss-Bonnet black holes and black strings. Special attention is paid to the evolution of massive fields in the background of various black holes. We have considered their quasi-normal ringing and the late-time tails. In addition, we present two new numerical techniques: a generalisation of the Nollert improvement of the Frobenius method for higher dimensional problems and a qualitatively new method, which allows to calculate quasi-normal frequencies for black holes, which metrics are not known analytically.

Journey to the $M_{\mathrm{BH}} - \sigma$ relation: the fate of low mass black holes in the Universe

Authors: Volonteri, Marta; Natarajan, Priyamvada

Eprint: http://xxx.lanl.gov/abs/0903.2262

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics

Abstract:

In this paper, we explore the establishment and evolution of the empirical correlation between black hole mass and velocity dispersion with redshift. We track the growth and accretion history of massive black holes starting from high redshift using two seeding models:(i) Population III remnants, and (ii) massive seeds from direct gas collapse. Although the seeds do not initially satisfy the $M_{\mathrm{BH}} - \sigma$ relation, the correlation is established and maintained at all times if self-regulating accretion episodes are associated with major mergers. The massive end of the $M_{\mathrm{BH}} - \sigma$ relation is established early, and lower mass MBHs migrate over time. How MBHs migrate toward the relation, the slope and the scatter of the relation all depend critically on the seeding model as well as the adopted self-regulation prescription. We expect flux limited AGN surveys and LISA to select accreting and merging MBHs respectively that have already migrated onto the $M_{\mathrm{BH}} - \sigma$ relation. This is a consequence of major mergers being more common at high redshift for the most massive, biased, galaxies that anchor the $M_{\mathrm{BH}} - \sigma$ relation early. We also predict the existence of a large population of low mass 'hidden' MBHs at high redshift which can easily

escape detection. Additionally, we find that if MBH seeds are massive, $\sim 10^5 M_\odot$, the low-mass end of the $M_{\rm BH} - \sigma$ flattens towards this asymptotic value, creating a characteristic "plume".

Signatures of the sources in the gravitational waves of a perturbed Schwarzschild black hole

Authors: Degollado, Juan Carlos

Eprint: http://xxx.lanl.gov/abs/0903.2073

Keywords: General Relativity and Quantum Cosmology

Abstract:

The explicit form of perturbation equation for the Ψ_4 Weyl scalar, containing the matter source terms, is derived for general type D spacetimes. It is described in detail the particular case of the Schwarzschild spacetime using in-going penetrating coordinates. As a practical application, we focused on the emission of gravitational waves when a black hole is perturbed by a surrounding dust-like fluid matter. The symmetries of the spacetime and the simplicity of the matter source allow, by means of a spherical harmonic decomposition, to study the problem by means of a one dimensional numerical code.

Constraining the Black Hole Mass Spectrum with Gravitational Wave Observations I: The Error Kernel

Authors: Plowman, Joseph E.; Jacobs, Daniel C.; Hellings, Ronald W.; Larson, Shane L.; Tsuruta, Sachiko

Eprint: http://xxx.lanl.gov/abs/0903.2059

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics

Abstract:

Many models have been suggested for the origin of the supermassive black holes (SMBHs) that are found in the centres of most galaxies. One class of models – the merger-tree models – typically predict a high-redshift population of intermediate-mass black holes (IMBHs), with between 100 and 100000 Solar Masses. A powerful way to observe these IMBHs is via gravitational waves the black holes emit as they merge. The statistics of the observed black hole population will allow us to discriminate between a merger tree and some other model, as well as between the various merger tree models themselves. However, gravitational wave detectors such as LISA will not be able to detect all such mergers nor assign precise black hole parameters to the merger, due to weak gravitational wave signal strengths. In order to use LISA observations to infer the statistics of the underlying population, these errors must be taken into account. We describe here a method for folding the LISA gravitational wave parameter error estimates into an 'error kernel' designed for use at the population model level. The effects of this error function are demonstrated by applying it to several recent models of black hole mergers, and some conclusions are made about LISA's ability to test models of the origin of supermassive black holes.

Probing Quiescent Massive Black Holes: Insights from Tidal Disruption Events

Authors: Gezari, Suvi; Strubbe, Linda; Bloom, Joshua S.; Grindlay, J. E.; Soderberg, Alicia; Elvis, Martin; Coppi, Paolo; Lawrence, Andrew; Ivezic, Zeljko; Merritt, David; Komossa, Stefanie; Halpern, Jules; Eracleous, Michael

Eprint: http://xxx.lanl.gov/abs/0903.1107

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics, Astrophysics - Galaxy Astrophysics

Abstract:

Tidal disruption events provide a unique probe of quiescent black holes in the nuclei of distant galaxies. The next generation of synoptic surveys will yield a large sample of flares from the tidal disruption of stars by massive black holes that will give insights to four key science questions: 1) What is the assembly history of massive black holes in the universe? 2) Is there a population of intermediate mass black holes that are the primordial seeds of supermassive black holes? 3) How can we increase our understanding of the physics of accretion onto black holes? 4) Can we localize sources of gravitational waves from the detection of tidal disruption events around massive black holes and recoiling binary black hole mergers?

An Efficient Pseudospectral Method for the Computation of the Self-force on a Charged Particle: Circular Geodesics around a Schwarzschild Black Hole

Authors: Cañizares, Priscilla; Sopuerta, Carlos F.

Eprint: http://xxx.lanl.gov/abs/0903.0505

Keywords: General Relativity and Quantum Cosmology, Astrophysics - High Energy Astrophysical Phenomena

Abstract:

The description of the inspiral of a stellar-mass compact object into a massive black hole sitting at a galactic centre is a problem of major relevance for the future space-based gravitational-wave observatory LISA (Laser Interferometer Space Antenna), as the signals from these systems will be buried in the data stream and accurate gravitational-wave templates will be needed to extract them. The main difficulty in describing these systems lies in the estimation of the gravitational effects of the stellar-mass compact object on his own trajectory around the massive black hole, which can be modeled as the action of a local force, the self-force. In this paper, we present a new time-domain numerical method for the computation of the self-force in a simplified model consisting of a charged scalar particle orbiting a nonrotating black hole. We use a multi-domain framework in such a way that the particle is located at the interface between two domains so that the presence of the particle and its physical effects appear only through appropriate boundary conditions. In this way we eliminate completely the presence of a small length scale associated with the need of resolving the particle. This technique also avoids the problems associated with the impact of a low differentiability of the solution in the accuracy of the numerical computations. The spatial discretization of the field equations is done by using the pseudospectral collocation method and the time evolution, based on the method of lines, uses a Runge-Kutta solver. We show how this special framework can provide very efficient and accurate computations in the time domain, which makes the technique amenable for the intensive computations required in the astrophysically-relevant scenarios for LISA.

Discrete derivative estimation in LISA Pathfinder data reduction

Authors: Ferraioli, Luigi; Hueller, Mauro; Vitale, Stefano

Eprint: http://xxx.lanl.gov/abs/0903.0324

Keywords: General Relativity and Quantum Cosmology, Physics - Data Analysis, Statistics and Probability

Abstract:

Data analysis for the LISA Technology package (LTP) experiment to be flown aboard the LISA Pathfinder mission requires the solution of the system dynamics for the calculation of the force acting on the test masses (TMs) starting from interferometer position data. The need for a solution to this problem has prompted us to implement a discrete time domain derivative estimator suited for the LTP experiment requirements. We first report on the mathematical procedures for the definition of two methods; the first based on a parabolic fit approximation and the second based on a Taylor series expansion. These two methods are then generalized and incorporated

in a more general class of five point discrete derivative estimators. The same procedure employed for the second derivative can be applied to the estimation of the first derivative and of a data smoother allowing defining a class of simple five points estimators for both. The performances of three particular realization of the five point second derivative estimator are analyzed with simulated noisy data. This analysis pointed out that those estimators introducing large amount of high frequency noise can determine systematic errors in the estimation of low frequencies noise levels.

Probing Stellar Dynamics in Galactic Nuclei

Authors: Miller, M. Coleman; Alexander, Tal; Amaro-Seoane, Pau; Barth, Aaron J.; Cutler, Curt; Gair, Jonathan R.; Hopman, Clovis; Merritt, David; Phinney, E. Sterl; Richstone, Douglas O.

Eprint: http://xxx.lanl.gov/abs/0903.0285

Keywords: Astrophysics - Galaxy Astrophysics, Astrophysics - Cosmology and Extragalactic Astrophysics

Abstract:

Electromagnetic observations over the last 15 years have yielded a growing appreciation for the importance of supermassive black holes (SMBH) to the evolution of galaxies, and for the intricacies of dynamical interactions in our own Galactic center. Here we show that future low-frequency gravitational wave observations, alone or in combination with electromagnetic data, will open up unique windows to these processes. In particular, gravitational wave detections in the $10^{-5} - 10^{-1}$ Hz range will yield SMBH masses and spins to unprecedented precision and will provide clues to the properties of the otherwise undetectable stellar remnants expected to populate the centers of galaxies. Such observations are therefore keys to understanding the interplay between SMBHs and their environments.

The Promise of Low-Frequency Gravitational Wave Astronomy

Authors: Prince, T. A.; for the LISA International Science Team

Eprint: http://xxx.lanl.gov/abs/0903.0103

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics, Astrophysics - High Energy Astrophysical Phenomena

Abstract:

This Astro2010 science white paper provides an overview of the opportunities in low-frequency gravitational-wave astronomy, a new field that is poised to make significant advances. While discussing the broad context of gravitational-wave astronomy, this paper concentrates on the low-frequency region (10^{-5} to 1 Hz), a frequency range abundantly populated in strong sources of gravitational waves including massive black hole mergers, ultra-compact stellar-mass galactic binaries, and capture of compact objects by massive black holes in the nuclei of galaxies.

Will Einstein Have the Last Word on Gravity?

Authors: Schutz, Bernard F.; Centrella, Joan; Cutler, Curt; Hughes, Scott A.

Eprint: http://xxx.lanl.gov/abs/0903.0100

Keywords: General Relativity and Quantum Cosmology

Abstract:

This is a whitepaper submitted to the 2010 Astronomy Decadal Review process, addressing the potential tests of gravity theory that could be made by observations of gravitational waves in the milliHertz frequency band by the proposed ESA-NASA gravitational wave observatory LISA. A key issue is that observations in this band of binary systems consisting of black holes offer very clean tests with high signal-to-noise ratios. Gravitational waves would probe nonlinear gravity and could reveal small corrections, such as extra long-range fields that arise in unified theories, deviations of the metric around massive black holes from the Kerr solution, massive gravitons, chiral effects, and effects of extra dimensions. The availability of strong signals from massive black hole binaries as well as complex signals from extreme mass-ratio binaries is unique to the milliHertz waveband and makes LISA a particularly sensitive probe of the validity of general relativity.

Finding and Using Electromagnetic Counterparts of Gravitational Wave Sources

Authors: Phinney, E. S.

Eprint: http://xxx.lanl.gov/abs/0903.0098

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics, Astrophysics - High Energy Astrophysical Phenomena

Abstract:

The principal goal of this whitepaper is not so much to demonstrate that gravitational wave detectors like LIGO and LISA will help answer many central questions in astronomy and astrophysics, but to make the case that they can help answer a far greater range of questions if we prepare to make the (sometimes substantial) effort to identify electromagnetic counterparts to the gravitational wave sources.

Massive Black Holes Across Cosmic Time

Authors: Madau, P.; Abel, T.; Bender, P.; Di Matteo, T.; Haiman, Z.; Hughes, S.; Loeb, A.; Phinney, E.; Primack, J.; Prince, T.; Rees, M.; Richstone, D.; Schutz, B.; Thorne, K.; Volonteri, M.

Eprint: http://xxx.lanl.gov/abs/0903.0097

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics, Astrophysics - High Energy Astrophysical Phenomena

Abstract:

This White Paper to the National Academy of Sciences Astro2010 Decadal Review Committee outlines some of the outstanding questions regarding the assembly history of Massive Black Holes in the nuclei of galaxies and the revolutionary contributions anticipated in this field from low-frequency gravitational wave astronomy.

An algorithm for detection of extreme mass ratio inspirals in LISA data

Authors: Babak, Stanislav; Gair, Jonathan R.; Porter, Edward K.

Eprint: http://xxx.lanl.gov/abs/0902.4133

Keywords: General Relativity and Quantum Cosmology, Astrophysics - Cosmology and Extragalactic Astrophysics

Abstract:

The gravitational wave signal from a compact object spiralling toward a massive black hole (MBH) is thought to be one of the most difficult sources to detect in the LISA data stream. Due to the large parameter space of possible signals and many orbital cycles spent in the sensitivity band of LISA, it has been estimated previously that of the order of 10^{35} templates would be required for a fully coherent search with a template grid, which is computationally impossible. Here we describe an algorithm based on a constrained Metropolis-Hastings stochastic search which allows us to find and accurately estimate parameters of isolated EMRI signals buried in Gaussian instrumental noise. We illustrate the effectiveness of the algorithm with results from searches of the Mock LISA Data Challenge round 1B data sets.

Nonlinear gravitational-wave memory from binary black hole mergers

Authors: Favata, Marc

Eprint: http://xxx.lanl.gov/abs/0902.3660

Keywords: Astrophysics - Solar and Stellar Astrophysics, General Relativity and Quantum Cosmology

Abstract:

Some astrophysical sources of gravitational-waves can produce a "memory effect," which causes a permanent displacement of the test masses in a freely-falling gravitational-wave detector. The Christodoulou memory is a particularly interesting nonlinear form of memory that arises from the gravitational-wave stress-energy tensor's contribution to the distant gravitational-wave field. This nonlinear memory contributes a non-oscillatory component to the gravitational-wave signal at leading (Newtonian-quadrupole) order in the waveform amplitude. Previous computations of the memory and its detectability considered only the inspiral phase of binary black hole coalescence. Using an "effective-one-body" (EOB) approach calibrated to numerical relativity simulations, as well as a simple fully-analytic model, the Christodoulou memory is computed for the inspiral, merger, and ringdown. The memory will be very difficult to detect with ground-based interferometers, but is likely to be observable in supermassive black hole mergers with LISA out to a redshift of two. Detection of the nonlinear memory could serve as an experimental test of the ability of gravity to "gravitate."

The gravitational wave background from star-massive black hole fly-bys

Authors: Toonen, Silvia; Hopman, Clovis; Freitag, Marc

Eprint: http://xxx.lanl.gov/abs/0902.3253

Keywords: Astrophysics - Earth and Planetary Astrophysics

Abstract:

Stars on eccentric orbits around a massive black hole (MBH) emit bursts of gravitational waves (GWs) at periapse. Such events may be directly resolvable in the Galactic centre. However, if the star does not spiral in, the emitted GWs are not resolvable for extra-galactic MBHs, but constitute a source of background noise. We estimate the power spectrum of this extreme mass ratio burst background (EMBB) and compare it to the anticipated instrumental noise of the Laser Interferometer

Space Antenna (LISA). To this end, we model the regions close to a MBH, accounting for mass-segregation, and for processes that limit the presence of stars close to the MBH, such as GW inspiral and hydrodynamical collisions between stars. We find that the EMBB is dominated by GW bursts from stellar mass black holes, and the magnitude of the noise spectrum $fS_GW^{1/2}$ is at least a factor ~ 10 smaller than the instrumental noise. As an additional result of our analysis, we show that LISA is unlikely to detect relativistic bursts in the Galactic centre.

Multi-Messenger Astronomy with GRBs: A White Paper for the Astro2010 Decadal Survey

Authors: Stamatikos, Michael; Gehrels, Neil; Halzen, Francis; Meszaros, Peter; Roming, Peter W. A.

Eprint: http://xxx.lanl.gov/abs/0902.3022

Keywords: Astrophysics - High Energy Astrophysical Phenomena, Astrophysics - Cosmology and Extragalactic Astrophysics

Abstract:

Gamma-ray Bursts (GRBs) are relativistic cosmological beacons of transient high energy radiation whose afterglows span the electromagnetic spectrum. Theoretical expectations of correlated neutrino and/or gravitational wave (GW) emission position GRBs at an astrophysical nexus for a metamorphosis in our understanding of the Cosmos. This new dawn in the era of experimental (particle) astrophysics and cosmology is afforded by current and planned facilities enabling the novel astronomies of high energy neutrinos and gravitational waves, in concert with unprecedented electromagnetic coverage. In this white paper, we motivate GRBs as a compelling scientific theme and highlight key technical advances that may facilitate fundamental breakthroughs in the context of Swift, Fermi, IceCube and LIGO (Laser Interferometer Gravitational Wave Observatory), whose capabilities would be augmented with JANUS (Joint Astrophysics Nascent Universe Satellite), EXIST (Energetic X-ray Imaging Survey Telescope) and LISA (Laser Interferometer Space Antenna). Scientific synergy will be achieved by leveraging the combined sensitivity of contemporaneous ground-based and satellite observatories, thus optimizing their collective discovery potential for: (i) revealing the origin(s) and acceleration mechanism(s) of cosmic rays, (ii) exposing GRB progenitor(s) and (iii) exploring the high-z Cosmos. Hence, the advent of GRB multi-messenger astronomy may cement an explicit connection to fundamental physics, via nascent cosmic windows, throughout the next decade and beyond.

Astro2010 Decadal Survey Whitepaper: Coordinated Science in the Gravitational and Electromagnetic Skies

Authors: Bloom, Joshua S.; Holz, Daniel E.; Hughes, Scott A.; Menou, Kristen; Adams, Allan; Anderson, Scott F.; Becker, Andy; Bower, Geoffrey C.; Brandt, Niel; Cobb, Bethany; Cook, Kem; Corsi, Alessandra; Covino, Stefano; Fox, Derek; Fruchter, Andrew; Fryer, Chris; Grindlay, Jonathan; Hartmann, Dieter; Haiman, Zoltan; Kocsis, Bence; Jones, Lynne; Loeb, Abraham; Marka, Szabolcs; Metzger, Brian; Nakar, Ehud; Nissanke, Samaya; Perley, Daniel A.; Piran, Tsvi; Poznanski, Dovi; Prince, Tom; Schnittman, Jeremy; Soderberg, Alicia; Strauss, Michael; Shawhan, Peter S.; Shoemaker, David H.; Sievers, Jonathan; Stubbs, Christopher; Tagliaferri, Gianpiero; Ubertini, Pietro; Wozniak, Przemyslaw

Eprint: http://xxx.lanl.gov/abs/0902.1527

Keywords: Astrophysics - Cosmology and Extra-Galactic Astrophysics, Astrophysics - High Energy Astrophysical Phenomena, General Relativity and Quantum Cosmology

Abstract:

It is widely expected that the coming decade will witness the first direct detection of gravitational waves (GWs). The ground-based LIGO and Virgo GW observatories are being upgraded to advanced sensitivity, and are expected to observe a significant binary merger rate. The launch of The Laser Interferometer Space Antenna (LISA) would extend the GW window to low frequencies, opening new vistas on dynamical processes involving massive ($M > 10^5 M_\odot$) black holes. GW events are likely to be accompanied by electromagnetic (EM) counterparts and, since information carried electromagnetically is complementary to that carried gravitationally, a great deal can be learned about an event and its environment if it becomes possible to measure both forms of radiation in concert. Measurements of this kind will mark the dawn of trans-spectral astrophysics, bridging two distinct spectral bands of information. The aim of this whitepaper is to articulate future directions in both theory and observation that are likely to impact broad astrophysical inquiries of general interest. What will EM observations reflect on the nature and diversity of GW sources? Can GW sources be exploited as complementary probes of cosmology? What cross-facility coordination will expand the science returns of gravitational and electromagnetic observations?

Discontinuous Galerkin method for computing gravitational waveforms from extreme mass ratio binaries

Authors: Field, Scott E.; Hesthaven, Jan S.; Lau, Stephen R.

Eprint: http://xxx.lanl.gov/abs/0902.1287

Keywords: General Relativity and Quantum Cosmology

Abstract:

Gravitational wave emission from extreme-mass-ratio binaries (EMRBs) should be detectable by the joint NASA-ESU LISA project, spurring interest in analytical and numerical methods for investigating EMRBs. We describe a discontinuous Galerkin (dG) method for solving the distributionally forced 1+1 wave equations which arise when modeling EMRBs via the perturbation theory of Schwarzschild blackholes. Despite the presence of jump discontinuities in the relevant polar and axial gravitational "master functions", our dG method achieves global spectral accuracy, provided that we know the instantaneous position, velocity, and acceleration of the small particle. Here these variables are known, since we assume that the particle follows a timelike geodesic of the Schwarzschild geometry. We document the results of several numerical experiments testing our method, and discuss the possible incorporation of radiation reaction in the model.

Effective-one-body waveforms calibrated to numerical relativity simulations: coalescence of non-spinning, equal-mass black holes

Authors: Buonanno, Alessandra; Pan, Yi; Pfeiffer, Harald P.; Scheel, Mark A.; Buchman, Luisa T.; Kidder, Lawrence E.

Eprint: http://xxx.lanl.gov/abs/0902.0790

Keywords: General Relativity and Quantum Cosmology

Abstract:

We calibrate the effective-one-body (EOB) model to an accurate numerical simulation of an equal-mass, non-spinning binary black-hole coalescence produced by the Caltech-Cornell collaboration. Aligning the EOB and numerical waveforms at low frequency over a time interval of 1000M, and taking into account the uncertainties in the numerical simulation, we investigate the significance and degeneracy of the EOB adjustable parameters during inspiral, plunge and merger, and determine the minimum number of EOB adjustable parameters that achieves phase and amplitude agreements on the order of the numerical error. We find that phase and fractional amplitude differences between the numerical and EOB values of the dominant gravitational wave mode h_{22} can be reduced to 0.02 radians and 2%, respectively, until a time 26 M before merger, and to 0.1 radians and 10%, at a time 16M after merger (during ringdown), respectively. Using LIGO, Enhanced LIGO and Advanced LIGO noise curves, we find that the overlap between the EOB and the numerical h_{22}, maximized only over the initial phase and time of arrival, is larger than 0.999 for equal-mass binary black holes with total mass 30-150 Msun. In addition to the leading gravitational mode (2,2), we compare the dominant subleading modes (4,4) and (3,2) and find phase and amplitude differences on the order of the numerical error. We also determine the mass-ratio dependence of one of the EOB adjustable parameters by fitting to numerical *inspiral* waveforms for black-hole binaries with mass ratios 2:1 and 3:1. These results improve and extend recent successful attempts aimed at providing gravitational-wave data analysts the best analytical EOB model capable of interpolating accurate numerical simulations.

An improved analytical description of inspiralling and coalescing black-hole binaries

Authors: Damour, Thibault; Nagar, Alessandro

Eprint: http://xxx.lanl.gov/abs/0902.0136

Keywords: General Relativity and Quantum Cosmology

Abstract:

We present an analytical formalism, within the Effective-One-Body framework, which predicts gravitational-wave signals from inspiralling and coalescing black-hole binaries that agree, within numerical errors, with the results of the currently most accurate numerical relativity simulations for several different mass ratios. In the equal-mass case, the gravitational wave energy flux predicted by our formalism agrees, within numerical errors, with the most accurate numerical-relativity energy flux. We think that our formalism opens a realistic possibility of constructing a sufficiently accurate, large bank of gravitational wave templates, as needed both for detection and data analysis of (non spinning) coalescing binary black holes.

Gravitational Waves from Eccentric Intermediate-Mass Black Hole Binaries

Authors: Amaro-Seoane, Pau; Miller, M. Coleman; Freitag, Marc

Eprint: http://xxx.lanl.gov/abs/0901.0604

Keywords: black hole physics, gravitational waves, methods: N-body simulations, stellar dynamics

Abstract:

If binary intermediate-mass black holes (IMBHs; with masses between 100 and $10^4 M_\odot$) form in dense stellar clusters, their inspiral will be detectable with the planned Laser Interferometer Space Antenna (LISA) out to several Gpc. Here, we present a study of the dynamical evolution of such binaries using a combination of direct N-body techniques (when the binaries are well separated) and three-body relativistic scattering experiments (when the binaries are tight enough that interactions with stars occur one at a time). We find that for reasonable IMBH masses there is only a mild effect on the structure of the surrounding cluster even though the binary binding energy can exceed the binding energy of the cluster. We demonstrate that, contrary to standard assumptions, the eccentricity in the LISA band can be in some cases as large as *sim* 0.2-0.3 and that it induces a measurable phase difference from circular binaries in the last year before merger. We also show that, even though energy input from the binary decreases the density of the core and slows down interactions, the total time to coalescence is short enough (typically less than a 100 million years) that such mergers will be unique snapshots of clustered star formation.

Searching for numerically-simulated signals of black hole binaries with a phenomenological template family

Authors: Santamaria, Lucia; Krishnan, Badri; Whelan, John T.

Eprint: http://xxx.lanl.gov/abs/0901.4696

Keywords: General Relativity and Quantum Cosmology

Abstract:

Recent progress in numerical relativity now allows computation of the binary black hole merger, whereas post-Newtonian and perturbative techniques can be used to model the inspiral and ringdown phases. So far, most gravitational-wave searches have made use of various post-Newtonian-inspired templates to search for signals arising from the coalescence of compact binary objects. Ajith et al have produced hybrid waveforms for non-spinning binary black-hole systems which include the three stages of the coalescence process, and constructed from them phenomenological templates which capture the features of these waveforms in a parametrized form. As a first step towards extending the present inspiral searches to higher-mass binary black-hole systems, we have used these phenomenological waveforms in a search for numerically-simulated signals injected into synthetic LIGO data as part of the NINJA project.

Testing gravitational-wave searches with numerical relativity waveforms: Results from the first Numerical INJection Analysis (NINJA) project

Authors: Aylott, Benjamin; Baker, John G.; Boggs, William D.; Boyle, Michael; Brady, Patrick R.; Brown, Duncan A.; Brügmann, Bernd; Buchman, Luisa T.; Buonanno, Alessandra; Cadonati, Laura; Camp, Jordan; Campanelli, Manuela; Centrella, Joan; Chatterji, Shourov; Christensen, Nelson; Chu, Tony; Diener, Peter; Dorband, Nils; Etienne, Zachariah B.; Faber, Joshua; Fairhurst, Stephen; Farr, Benjamin; Fischetti, Sebastian; Guidi, Gianluca; Goggin, Lisa M.; Hannam, Mark; Herrmann, Frank; Hinder, Ian; Husa, Sascha; Kalogera, Vicky; Keppel, Drew; Kidder, Lawrence E.; Kelly, Bernard J.; Krishnan, Badri; Laguna, Pablo; Lousto, Carlos O.; Mandel, Ilya; Marronetti, Pedro; Matzner, Richard; McWilliams, Sean T.; Matthews, Keith D.; Mercer, R. Adam; Mohapatra, Satyanarayan R. P.; Mroué, Abdul H.; Nakano, Hiroyuki; Ochsner, Evan; Pan, Yi; Pekowsky, Larne; Pfeiffer, Harald P.; Pollney, Denis; Pretorius, Frans; Raymond, Vivien; Reisswig, Christian; Rezzolla, Luciano; Rinne, Oliver; Robinson, Craig; Röver, Christian; Santamaría, Lucía; Sathyaprakash, Bangalore; Scheel, Mark A.; Schnetter, Erik; Seiler, Jennifer; Shapiro, Stuart L.; Shoemaker, Deirdre; Sperhake, Ulrich; Stroeer, Alexander; Sturani, Riccardo; Tichy, Wolfgang; Liu, Yuk Tung; van der Sluys, Marc; van Meter, James R.; Vaulin, Ruslan; Vecchio, Alberto; Veitch, John; Viceré, Andrea; Whelan, John T.; Zlochower, Yosef

Eprint: http://xxx.lanl.gov/abs/0901.4399

Keywords: General Relativity and Quantum Cosmology

Abstract:

The Numerical INJection Analysis (NINJA) project is a collaborative effort between members of the numerical relativity and gravitational-wave data analysis communities. The purpose of NINJA is to study the sensitivity of existing gravitational-wave search algorithms using numerically generated waveforms and to foster closer collaboration between the numerical relativity and data analysis communities. We describe the results of the first NINJA analysis which focused on gravitational waveforms from binary black hole coalescence. Ten numerical relativity groups contributed numerical data which were used to generate a set of gravitational-wave signals. These signals were injected into a simulated data set, designed to mimic the response of the Initial LIGO and Virgo gravitational-wave detectors. Nine groups analysed this data using search and parameter-estimation pipelines. Matched filter algorithms, un-modelled-burst searches and Bayesian parameter-estimation and model-selection algorithms were applied to the data. We report the efficiency of these search methods in detecting the numerical waveforms and measuring their parameters. We describe preliminary comparisons between the different search methods and suggest improvements for future NINJA analyses.

Status of black-hole-binary simulations for gravitational-wave detection

Authors: Hannam, Mark

Eprint: http://xxx.lanl.gov/abs/0901.2931

Keywords: General Relativity and Quantum Cosmology

Abstract:

It is now possible to theoretically calculate the gravitational-wave signal from the inspiral, merger and ringdown of a black-hole-binary system. The late inspiral, merger and ringdown can be calculated in full general relativity using numerical methods. The numerical waveforms can then be either stitched to inspiral waveforms predicted by approximation techniques (in particular post-Newtonian calculations) that start at an arbitrarily low frequency, or used to calibrate free parameters in analytic models of the full waveforms. In this review I summarize the status of numerical-relativity (NR) waveforms that include at least ten cycles of the dominant mode of the GW signal before merger, which should be long enough to produce accurate, complete waveforms for GW observations.

Linearized SQUID Array (LISA) for High Bandwidth Frequency-Domain Readout Multiplexing

Authors: Lanting, T.; Dobbs, M.; Spieler, H.; Lee, A. T.; Yamamoto, Y.

Eprint: http://xxx.lanl.gov/abs/0901.1919

Keywords: Astrophysics - Instrumentation and Methods for Astrophysics, Physics - Instrumentation and Detectors

Abstract:

We have designed and demonstrated a Superconducting Quantum Interference Device (SQUID) array linearized with cryogenic feedback. To achieve the necessary loop gain a 300 element series array SQUID is constructed from three monolithic 100-element series arrays. A feedback resistor completes the loop from the SQUID output to the input coil. The short feedback path of this Linearized SQUID Array (LISA) allows for a substantially larger flux-locked loop bandwidth as compared to a SQUID flux-locked loop that includes a room temperature amplifier. The bandwidth, linearity, noise performance, and dynamic range of the LISA are sufficient for its use in our target application: the multiplexed readout of transition-edge sensor bolometers.

The Galactic Gravitational wave foreground

Authors: Nelemans, G.

Eprint: http://xxx.lanl.gov/abs/0901.1778

Keywords: Astrophysics - Solar and Stellar Astrophysics, Astrophysics - Galactic Astrophysics, General Relativity and Quantum Cosmology

Abstract:

I present an overview of the Galactic binaries that form the foreground for the ESA/NASA Laser Interferometer Space Antenna (LISA). The currently known population is discussed, as well as current and near-future large-scale surveys that will find new systems. The astrophysics that can be done when the LISA data becomes available is presented, with particular attention to verification binaries, the overall Galactic populations, neutron star and black hole binaries and sources in globular clusters. I discuss the synergy with electro-magnetic observations and correct an error in the estimate of the number of LISA systems that can be found in the optical compared to Nelemans (2006a) and conclude that at least several hundreds of systems should be detectable.

Extreme mass ratio inspiral rates: dependence on the massive black hole mass

Authors: Hopman, Clovis

Eprint: http://xxx.lanl.gov/abs/0901.1667

Keywords: Astrophysics - Galactic Astrophysics, Astrophysics - Cosmology and Extra-Galactic Astrophysics

Abstract:

We study the rate at which stars spiral into a massive black hole (MBH) due to the emission of gravitational waves (GWs), as a function of the mass M of the MBH. In the context of our model, it is shown analytically that the rate approximately depends on the MBH mass as $M^{-1/4}$. Numerical simulations confirm this result, and show that for all MBH masses, the event rate is highest for stellar black holes, followed by white dwarfs, and lowest for neutron stars. The Laser Interferometer Space Antenna (LISA) is expected to see hundreds of these extreme mass ratio inspirals per year. Since the event rate derived here formally diverges as M->0, the model presented here cannot hold for MBHs of masses that are too low, and we discuss what the limitations of the model are.

Numerical black hole initial data with low eccentricity based on post-Newtonian orbital parameters

Authors: Walther, Benny; Bruegmann, Bernd; Mueller, Doreen

Eprint: http://xxx.lanl.gov/abs/0901.0993

Keywords: General Relativity and Quantum Cosmology

Abstract:

Black hole binaries on non-eccentric orbits form an important subclass of gravitational wave sources, but it is a non-trivial issue to construct numerical initial data with minimal initial eccentricity for numerical simulations. We compute post-Newtonian orbital parameters for quasi-spherical orbits using the method of Buonanno, Chen and Damour (2006) and examine the resulting eccentricity in numerical simulations. Four different methods are studied resulting from the choice of Taylor-expanded or effective-one-body Hamiltonians, and from two choices for the energy flux. The eccentricity increases for unequal masses and for spinning black holes, but remains smaller than that obtained from previous post-Newtonian approaches. The effective-one-body Hamiltonian offers advantages for decreasing initial separation as expected, but in the context of this study also performs significantly better than the Taylor-expanded Hamiltonian for binaries with spin.

Gravitational waves from an early matter era

Authors: Assadullahi, Hooshyar; Wands, David

Eprint: http://xxx.lanl.gov/abs/0901.0989

Keywords: Astrophysics - Cosmology and Extra-Galactic Astrophysics, General Relativity and Quantum Cosmology, High Energy Physics - Phenomenology

Abstract:

We investigate the generation of gravitational waves due to the gravitational instability of primordial density perturbations in an early matter-dominated era which could be detectable by experiments such as LIGO and LISA. We use relativistic perturbation theory to give analytic estimates of the tensor perturbations generated at second order by linear density perturbations. We find that large enhancement factors with respect to the naive second-order estimate are possible due to the growth of density perturbations on sub-Hubble scales. However very large enhancement factors coincide with a breakdown of linear theory for density perturbations on small scales. To produce a primordial gravitational wave background that would be detectable with LIGO or LISA from density perturbations in the linear regime requires primordial comoving curvature perturbations on small scales of order 0.02 for Advanced LIGO or 0.005 for LISA, otherwise numerical calculations of the non-linear evolution on sub-Hubble scales are required.