2 Astrophysics and General Relativity

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Astrophysics could be defined as the branch of physics where gravity is important. For much of astrophysics, Newtonian gravity is adequate, but for phenomena involving very strong gravitational fields, cosmological distances, the effect of gravity on light, or just extremely precise measurements, relativistic gravity is needed. After a hundred years, Einsteinian gravity continues to pass all tests, and meanwhile reveals new manifestations. Exploring these is the area of our research.

2.1 Gravitational waves and LISA

Although the existence of gravitational waves (GW) can be inferred indirectly, from the spin-down of binary pulsar systems, the first direct detection of gravitational waves is an eagerly-awaited event. Within our group we addressed various topics on gravitational wave physics.

Motivated by a recently proposed parameterized post-Einsteinian (ppE) scheme, which introduces corrections to the post-Newtonian coefficients of the frequency domain gravitational waveform in order to emulate alternative theories of gravity, we computed analytical time domain waveforms that, after a numerical Fourier transform, aim to represent (phase corrected only) ppE waveforms. In this formalism, alternative theories manifest themselves via corrections to the phase and frequency, as predicted by General Relativity (GR), at different post-Newtonian (PN) orders. In order to present a generic test of alternative theories of gravity, we assumed that the coupling constant of each alternative theory is manifestly positive, allowing corrections to the GR waveforms to be either positive or negative. By exploring the capabilities of massive black hole binary GR waveforms in the detection and parameter estimation of corrected time domain ppE signals, using the current proposed eLISA configuration, we demonstrated that for corrections arising at higher than 1 PN order in phase and frequency, GR waveforms are sufficient for both detecting and estimating the parameters of alternative theory signals. However, for theories introducing corrections at the 0 and 0.5 PN order, GR waveforms are not capable of covering the entire parameter space, requiring the use of non-GR waveforms for detection and parameter estimation.

Compact binaries in hyperbolic orbits are plausible GW sources for the upcoming and planned GW observatories. We developed an efficient prescription to compute post-Newtonian (PN) accurate ready-to-use GW polarization states for spinning compact binaries, influenced by the dominant order spin-orbit interactions, in hyperbolic orbits. This is achieved by invoking the 1.5 PN accurate quasi-Keplerian parameterization for the radial sector of the orbital dynamics. We probed the influences of spins and gravitational radiation reaction on h_+ and h_x during the hyperbolic passage. It turns out that both polarization states exhibit the memory effect for GWs from spinning compact binaries in hyperbolic orbits. In contrast, only cross polarization state exhibits the memory effect for GWs from non-spinning compact binaries. Additionally, we computed 1 PN accurate amplitude corrected GW polarization states for hyperbolic non-spinning compact binaries in a fully parametric manner and performed initial comparisons with the existing waveforms.

We proposed a way of including the next-to-leading (NLO) order spin-spin coupling into an effective-one-body (EOB) Hamiltonian, extending our work, which was restricted to the case of equatorial orbits and aligned spins, to general orbits with arbitrary spin orientations. To achieve this goal we applied appropriate canonical phase-space transformations to the NLO spin-spin Hamiltonian in Arnowitt-Deser-Misner (ADM) coordinates, and systematically added effective quantities at NLO to all spin-squared terms appearing in the EOB Hamiltonian. As required by consistency, the introduced quantities reduce to zero in the test-mass limit. We exposed the result both in a general gauge and in a gauge-fixed form, chosen to minimize the number of new coefficients that have to be inserted into the effective spin squared. As a result, the 25 parameters that describe the ADM NLO spin-spin dynamics get condensed into only 12 EOB terms.

We studied binary neutron star mergers using nonlinear 3+1 numerical relativity simulations and the analytical effective-one-body (EOB) model. The EOB model predicts quasi-universal relations between the mass-rescaled GW frequency and the binding energy at the moment of merger, and certain dimensionless binary tidal coupling constants depending on the stars Love numbers, compactnesses and the binary mass ratio. These relations are quasi-universal in the sense that, for a given value of the tidal coupling constant, they do not depend significantly on the equation of state and on the mass ratio, though they do depend on stars spins. The spin dependence is approximately linear for small spins aligned with the orbital angular momentum. The quasi-universality is a property of the conservative dynamics; nontrivial relations emerge as the binary interaction becomes tidally dominated. This analytical prediction is qualitatively consistent with new, multi-orbit numerical relativity results for the relevant case of equal-mass irrotational binaries. Universal relations are thus expected to characterize neutron star mergers dynamics. In the context of GW astronomy, these universal relations may be used to constrain the neutron star equation of state using waveforms that model the merger accurately.

2.1.1 LISA Pathfinder

We are member of the LISA Pathfinder science team and of the eLISA consortium board. LISA Pathfinder (see Fig. 2.1) is a dedicated technology demonstrator for the evolved Laser Interferometer Space Antenna (eLISA) ESA mission. The technologies required for eLISA are extremely challenging. LISA Pathfinder essentially mimics one arm of the eLISA constellation by shrinking the 1 million kilometer arm length down to a few tens of centimeters, giving up the sensitivity to gravitational waves, but keeping the measurement technology: the distance between the two test masses is measured using a laser interferometric technique similar to one aspect of the eLISA interferometry system. The scientific objective of the LISA Pathfinder mission consists then of the first in-flight test of low frequency gravitational wave detection metrology. LISA Pathfinder is currently under final integration and tests and is scheduled to be launched in fall 2015 to the L1 Sun-Earth point in space.

FIG. 2.1 – LISA-Pathfinder at the top of the propulsion module which will bring it at the L1 point (first Sun-Earth Lagrange point).

2.2 Gravitational Lensing

That gravitational lensing — specifically that light is affected by both space and time parts of the metric, unlike Newtonian bodies, which are affected only by the time part — is too well known to need elaborating here. Nowadays, however, gravitational lensing is valued, more than as a test of general relativity, as a way of detecting matter that would be otherwise invisible.

On the scale of galaxies and clusters of galaxies, gravitational lensing is very important as a probe of dark matter. Extracting the information on mass distributions, however, requires solving a non-trivial inverse problem. R. Küng, I. Mohammed and P. Saha, together with external collaborators, have worked on the problem of mapping a mass distribution from lensing observables. One part of this work is the development of an improved method for modeling galaxy lenses and furthermore, a theoretical formulation and computational interface to enable modeling in a citizen-science context. The other aspect is mapping and interpreting dark-matter structure in strong-lensing galaxy-clusters

2.2.1 Microlensing

We studied the polarization of the star light that may arise during microlensing events due to the high gradient of magnification across the atmosphere of the source star, by exploring the full range of microlensing and stellar physical parameters. Since it is already known that only cool evolved giant stars give rise to the highest polarization signals, we computed the polarization as due to the photon scattering on dust grains in the stellar wind. Motivated by the possibility to perform a polarization measurement during an ongoing microlensing event, we considered the recently reported event catalog by the OGLE collaboration covering the 2001-2009 campaigns (OGLE-III events), that makes available the largest and more comprehensive set of single lens microlensing events towards the Galactic bulge. The study of these events, integrated by a Monte Carlo analysis, allowed us to estimate the expected polarization profiles and to predict for which source stars and at which time it is most convenient to perform a polarization measurement in an ongoing event. We found that about two dozens of OGLE-III events (about 1 percent of the total) have maximum degree of polarization in the range $0.1\% < P_{max} < 1\%$, corresponding to source stars with apparent magnitude $I \leq 14.5$, being very cool red giants. This signal is measurable by using the FORS2 polarimeter at VLT telescope with about 1 hour integration time.

2.3 Space clocks and relativity

A surprising natural orbiting clock is provided by stars in orbit around a black hole at the centre of our Galaxy. Some of these stars are on very eccentric orbits, and around their point of closest approach to the black hole, they move at a few percent of light speed. The spectra of these stars should exhibit effects of space curvature and black-hole spin. R. Angèlil and P. Saha have studied the relevant observational signatures, and how they could be disentangled from the Newtonian effects of other stars and gas in the Galactic-centre region.

We computed the PPN parameters γ and β for general scalar-tensor theories in the Einstein frame, which we compared to the existing PPN formulation in the Jordan frame for alternative theories of gravity. This computation is important for scalar-tensor theories that are expressed in the Einstein frame, such as chameleon and symmetron theories, which can incorporate hiding mechanisms that predict environment-dependent PPN parameters. We introduced a general formalism for scalar-tensor theories which is constrained by the limit on γ given by the Cassini experiment. In particular we discussed massive Brans-Dicke scalar fields for extended sources. Next, using a recently proposed Earth satellite experiment in which atomic clocks are used for spacecraft tracking, we computed the observable perturbations in the redshift induced by PPN parameters deviating from their general relativistic values.

We studied in detail the scientific objectives in fundamental physics of the Space-Time Explorer and Quantum Equivalence Space Test (STE-QUEST) mission, which was proposed within the framework of the ESA call for missions. It carries out tests of different aspects of the Einstein Equivalence Principle using atomic clocks, matter wave interferometry and long distance time/frequency links, providing fascinating science at the interface between quantum mechanics and gravitation that cannot be achieved, at that level of precision, in ground experiments. We discussed the strong interest of performing equivalence principle tests in the quantum regime, i.e. using quantum atomic wave interferometry.