2 Astrophysics and General Relativity

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For describing most of astrophysical phenomena, Newtonian gravity is adequate, but for situations involving very strong gravitational fields, or cosmological distances, or 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 thrown at it, and meanwhile reveals new manifestations as the first direct detection of gravitational waves. Exploring these is the area of our research.

2.1 Gravitational waves and LISA

This year saw very exciting developments in our field: on 3 December 2015 LISA Pathfinder was successfully launched in orbit from Kourou and reaching L1 Lagrange point around 22 January 2016. The satellite is since then performing as designed.

On 11 February 2016 the LIGO collaboration announced the first direct detection of a gravitational wave signal, originating from the coalescence of two black holes of about 30 solar masses each [1]. This discovery opens without any doubt a new window in the observation of the Universe. Although the existence of gravitational waves had been inferred indirectly, from the spin-down of binary pulsar systems, the first direct detection was an eagerly-awaited event, which took place 100 years after Einstein's final formulation of general relativity and his prediction of gravitational waves. Clearly, these developments will speed up the implementation of the LISA project, aimed to build a space-based observatory for gravitational waves at lower frequency than the Earth-based LIGO detectors. Within our group we addressed various topics on gravitational wave physics.

Simone Balmelli studied the problem of how to incorporate spin effects in the effective-one-body (EOB) approach used to compute in a semi-analytical way the complete waveform emitted during a coalescing process of two massive compact bodies, such as black holes or neutron-stars. He constructed the EOB Hamiltonian with next-to-leading order spin-spin coupling for two non-precessing black holes in the special case of aligned spin. Indeed, by adding a term of fractional 1 PN (post-Newtonian) order to the effective Kerr parameter squared of previously developed EOB models, it was possible to reproduce the next-to-leading order, spin-spin contribution of the PN expanded Hamiltonian for two black holes with spins aligned with the angular momentum vector. To achieve this a special canonical transformation quadratic in the spins had to be added to all the transformations used before in the literature. The additional spin-squared term vanishes whenever the mass-ratio tends to zero, so as to correctly reproduce the exact Kerr dynamics. As next the dynamics of circular orbits in the case of equal masses and spins has been evaluated. It was shown that the effective radial potential still preserves the usual structure, reproducing local minima and maxima, corresponding to stable and unstable orbits. These results were then generalized to the case with arbitrary spin orientations. This was possible by implementing the spin-spin terms after a suitable canonical phase-space transformation of the corresponding ADM Hamiltonian.

FIG. 2.1 –
LISA Pathfinder lift-off on VV06
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In a joint work of Simone Balmelli with Thibault Damour (from the Institut des Hautes Etudes Scientifiques located in Bures-sur-Yvette, France), they presented a new EOB Hamiltonian with next-to-leading order (NLO) spin-spin coupling for black hole binaries endowed with arbitrarily oriented spins. The Hamiltonian is based on the model for parallel spins and equatorial orbits previously developed, but differs from it in several ways. In particular, the NLO spin-spin coupling is not incorporated by a redefinition of the centrifugal radius r_C, but by separately modifying certain sectors of the Hamiltonian, which are identified according to their dependence on the momentum vector. We follow a gauge-fixing procedure, which allows to reduce the 25 different terms of the NLO spin-spin Hamiltonian in Arnowitt-Deser-Misner coordinates to only 9 EOB terms. This is an improvement with respect to a EOB model recently proposed, where 12 EOB terms were involved. Another important advantage is the remarkably simple momentum structure of the spin-spin terms in the effective Hamiltonian, which is simply quadratic up to an overall square root.

Lorenzo De Vittori developed a prescription to generate accurate gravitational wave signals from hyperbolic collisions of compact objects, like black holes or neutron stars. The methods developed by Lorenzo are valid for arbitrary eccentricities and masses of the colliding objects, and take into account radiation reaction effects and spin precession, as due to spin-orbit coupling correction terms. He studied in detail the gravitational wave forms from spinning compact binaries in hyperbolic orbits. In this work an efficient prescription to compute PN accurate gravitational wave polarization states for spinning compact binaries was developed. In hyperbolic encounters the dominant contribution comes from the spin-orbit interaction, which is taken into account up to 1.5 PN. It turns out that both polarization states exhibit the memory effect for gravitational waves from spinning compact binaries in hyperbolic orbits. In particular, an explicit expression for the memory effect was derived in the two polarization states up to first PN order and related to the general Liénard-Wiechert solution for the linearized field equations of unbound systems. Furthermore, some estimates for its possible observation with eLISA were discussed. Gravitational waveforms for precessing eccentric comparable-mass binaries were computed up to second PN. As an expansion parameter eccentricity was used. These gravitational waveforms are of relevance for the future eLISA mission.

The detection of gravitational waves and the corresponding determination of polarization modes is a powerful tool to discriminate between general relativity and alternative theories of gravity such as $f(R)$ theories. Working within the framework of the linearized approach, Rizwana Kausar and Lionel Philippoz investigated the polarization of gravitational waves in $f(R)$ theories, both in the metric and the Palatini formalisms. Besides the usual two transverse-traceless tensor modes present in general relativity, there are in general two additional scalar ones: a massive longitudinal mode and a massless transverse mode (the so-called breathing mode). This last mode has often been overlooked in the literature, due to the assumption that, in $f(R)$, the application of the Lorenz gauge also leads to transverse traceless wave solutions. We however show that this is in general not possible and, in particular, that the traceless condition cannot be imposed. Our findings are in agreement with the results found in the literature using the Newman-Penrose formalism, and thus clarify the inconsistencies found so far.

2.1.1 LISA Pathfinder

We are member of the LISA Pathfinder science team and of the eLISA consortium board. LISA Pathfinder 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 has been successfully launched by a Vega rocket on 3 December 2015 from the ESA spaceport in Kourou. On 22 January 2016 it arrived at L1 Sun-Earth Lagrange point in space. On 15 and 16 February both test masses have been successfully released and since beginning of March has started its science mission. The satellite now works as designed.

[1] B.P. Abbott *et al.*, LIGO and Virgo Collaborations, Phys. Rev. Lett. 116, 061102, 2016.

2.2 Gravitational Lensing

Gravitational lensing – specifically that light is affected by both space and time parts of the metric, unlike Newtonian bodies, which are affected by the time part only – needs no elaborations here. Nowadays, gravitational lensing is valued rather 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

2.3 Space clocks and relativity

Together with S. Lecomte from CSEM in Neuchâtel, M. Rothacher from ETH Zürich, Q. Wang and P. Rochat from Spectratime in Neuchâtel and some of their collaborators we conducted a study on behalf of the Swiss Space Office (SSO) for a satellite mission called E-GRIP (Einstein Gravitational Red-shIft Probe) to test general relativity using an onboard hydrogen maser. The clock would be sensitive to 2×10^{-6} the level of the Earth's gravitational redshift, and would be sensitive to space-curvature around the Earth and frame-dragging by the Earth's spin. In addition, E-GRIP would provide a wealth of science for time and frequency metrology- and geodesy. We delivered by December 2015 a detailed report and on 11 December it has been presented at SSO in Bern. We have been requested to study this proposal further.

2.4 Atomic clocks applications in geophysics

According to general relativity, a clock experiencing a shift in the gravitational potential ΔU will measure a frequency change given by $\Delta f/f \approx \Delta U/c^2$. The best clocks are optical clocks. After about 7 hours of integration they reach stabilities of $\Delta f/f \sim 10^{-18}$ and can be used to detect changes in the gravitational potential that correspond to vertical displacements of the centimeter level. At this level of performance, ground-based atomic clock networks emerge as a tool that is complementary to existing technology for monitoring a wide range of geophysical processes by directly measuring changes in the gravitational potential. Vertical changes of the clock's position due to magmatic, post-seismic or tidal deformations can result in measurable variations in the clock tick rate. In this work Ruxandra Bondarescu and Andreas Schärer together with further authors computed the geopotential change arising due to an inflating magma chamber using the Mogi model and applied it to the Etna volcano. Its effect on an observer on the Earth's surface can be divided into two different terms: one purely due to uplift (free-air gradient) and one due to the redistribution of matter. Thus, with the centimeter-level precision of current clocks it is already possible to monitor volcanoes. The matter redistribution term is estimated to be 3 orders of magnitude smaller than the uplift term. Additionally, clocks can be compared over distances of thousands of kilometers over short periods of time, which improves our ability to monitor periodic effects with long wavelength like the solid Earth tide.