3 Astrophysics and General Relativity

Y. Boetzel, P. Denzel, M. Haney, W. Ishibashi, Ph. Jetzer, R. Küng, A. Schärer,
L. Philippoz, P. Saha, J. Su, J. ten Pierick

Newtonian gravity is adequate for most astrophysical phenomena, but for situations involving very strong gravitational fields (or cosmological distances, or the effect of gravity on light, or simply extremely precise measurements), relativistic gravity is needed. After more than a hundred years, Einsteinian gravity continues to pass all tests thrown at it, and meanwhile reveals new insights into the Universe through the recent observations of gravitational waves (GW). Exploring various aspects of general relativity (GR) is our area of research.

3.1 Gravitational Waves

One of the predictions of GR is the existence of GW. In analogy to electromagnetism, accelerating masses cause local perturbations in spacetime geometry that propagate at the speed of light. Indirect observational evidence for GW has existed since 1974, through the measurements of the orbital decay of binary pulsars like the Hulse-Taylor pulsar (PSR B1913+16). Efforts to directly measure the extremely tiny effects of a passing GW on Earth have been ongoing since the 1960s, with the development of resonant bar detectors and subsequently laser interferometry. On 14 September 2015, the two instruments of the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected the GW signal GW150914 from the inspiral and subsequent merger of two stellar-mass black holes, marking the first direct detection of GW and the first observation of a binary black hole merger. Further black hole coalescing events have been detected since then, in joint observation with the European Virgo detector. In October 2017, the LIGO-Virgo collaborations and their partner observatories announced the first joint observation of a neutron star merger in GW and the electromagnetic spectrum, inaugurating a new era in multi-messenger astronomy. As a member of the LIGO Scientific Collaboration (LSC) and as part of the LISA Pathfinder (LPF) and Laser Interferometer Space Antenna (LISA) science teams, our group is directly involved in the efforts of both ground-based and space-borne GW observatories.

3.1.1 LISA Pathfinder

Ph. Jetzer is member of the LISA Pathfinder (LPF) Science Working Team, of the LISA Consortium Board and of the ESA LISA Science Study Team. LISA Pathfinder is a European Space Agency (ESA) mission launched on December 3, 2015. The mission has terminated in July 2017. LPF's goal was to place two test masses in a nearly perfect gravitational free-fall, and control and measure their relative motion with unprecedented accuracy, at the level required for a future space-based gravitational wave (GW) observatory, such as LISA (see Fig. 3.1). The latest results have been published in February 2018 and show an improvement with respect to the previous ones.

The demonstration of the LPF's key technologies opens the door to the development of LISA, which will be capable of detecting gravitational waves emanating from a wide range of objects in the universe. In November 2013, ESA selected *The Gravitational Universe* as the science theme to be explored by ESA's Large class mission L3. Following the success of LPF, the Laser Interferometer Space Antenna (LISA) was selected as the L3 mission by ESA in June 2017.

3.1.2 Gravitational Waves, LIGO and LISA

The scope of LISA is to detect and study low-frequency GW from about 0.1 mHz to 1 Hz, thus complementing ground-based gravitational observatories. LISA opens

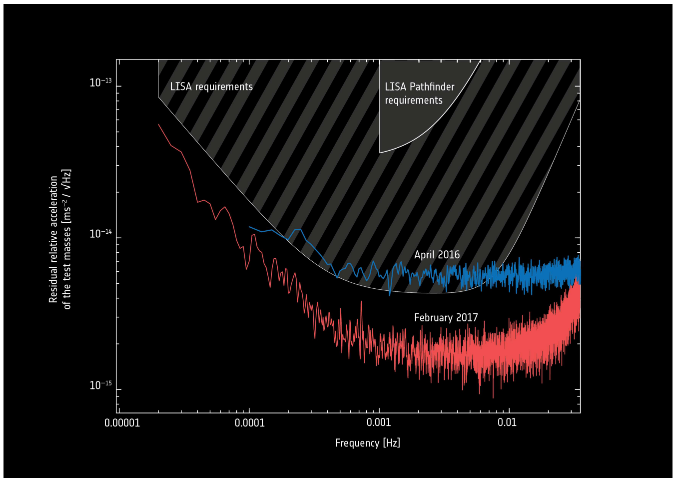

Fig. 3.1 – Analysis of the LISA Pathfinder mission results towards the end of the mission (red line) compared with the first results published shortly after the spacecraft began science operations (blue line). The initial requirements (top, wedge-shaped area) and that of the future GW detection mission LISA (middle, striped area) are included for comparison, and show that it far exceeded expectations. Copyright ESA/LISA Pathfinder collaboration.

new possibilities for astrophysical studies by allowing, for instance, to detect supermassive black holes (typically of $10^6 - 10^7\ M_\odot$) merging at cosmological distances. Mergers of a supermassive black hole with another compact object (such as another black hole or a neutron star) produce a very clean GW signal which LISA will be able to measure with high precision. Alternative gravity theories would influence the dynamics of such mergers, and hence LISA is expected either to directly see the imprints of certain alternative theories or to put severe constraints on them. Another class of objects, which will be observed by LISA, are ultra-compact binaries, in particular binaries of white dwarfs in our Galaxy. They are important sources of GW in the mHz frequency range. Moreover, it will be possible to detect or put strong constraints on the primordial GW background, which – as the cosmic microwave background – is a leftover from the Big Bang.

Members of our group are working on various theoretical aspects of LISA-related GW science. As members of the LIGO Scientific Collaboration (LSC), we are contributing to the theoretical groundwork for the LIGO-Virgo detectors and are directly involved in the analysis of GW data.

According to GR, GW possess two tensor polarizations. Deviation from GR can however lead to the appearance of additional modes: up to two scalar ones (a massive longitudinal mode and a massless transverse mode), as well as two vector modes. Detecting (or not) such additional modes can be a powerful tool to test GR and put constraints on alternative theories of gravity. Lionel Philippoz is investigating the limits that could be provided on the various polarization modes by several configurations of LISA, as well as correlations of Earth-based and space-borne detectors which have been proposed in the past years, and the possibilities to extract that information from a given GW signal. This study focus primarily on a stochastic GW background which could originate from the early universe, and better constraints on that signal are of importance for cosmology. In his master thesis, Adrian Boîtier studied the future GW detectors ET and DECIGO and their inclusion in a network of existing detectors in order to establish the sensitivity curves for the various polarization modes of GW, in the case of a GW background and point sources.

Yannick Boetzel is studying theoretical aspects of GW from compact binaries in eccentric inspiralling orbits. In particular he could already provide an elegant analytic solution to the 3PN-accurate Kepler equation, associated with the 3PN-accurate generalized quasi-Keplerian parameterization for compact binaries in eccentric orbits. This is an important step to model accurate GW templates from compact binaries in inspiralling eccentric orbits. For his master thesis, Michael Ebersold studied the Hansen coefficients, used to describe the Keplerian motion of binary systems, in a post-Newtonian setting.

In March 2017, Philippe Jetzer, Maria Haney and Yannick Boetzel joined the GEO600 collaboration and were subsequently approved for membership in the LIGO Scientific Collaboration (LSC), establishing the first LSC group in Switzerland. We have committed a contribution to LSC research that includes template waveform development for the GW search and parameter estimation efforts, as well as tests of GR with GW data from binary black hole mergers. At present, Y. Boetzel and M. Haney have (respectively) promised 50% and 90% of their research time to LSC-approved projects, with Ph. Jetzer serving as the PI of the group. A focus of our LSC work is the development of accurate and efficient GW templates, as well as studying their implications for improved GW search and parameter estimation methods. In particular, we model GW signals that take previously unmodeled effects like spin precession and orbital eccentricity of compact binary GW sources into account, broadening the parameter space for GW searches and eliminating systematic biases in GW source parameter estimation. Additionally, we develop new data analysis pipelines that aim to test and constrain possible strong-field deviations from GR with GW data.

A number of recent investigations have explored several plausible astrophysical mechanisms for the formation and merger of LIGO relevant compact binaries which retain non-negligible eccentricities throughout their lifetime, through dynamical-formation scenarios that take place in dense stellar environments. These investigations suggest that $\sim 1\%$ of all black hole binary mergers could be detected with non-negligible eccentricity, and that ground-based GW observatories could potentially detect up to 10 eccentric inspirals per year up to redshift $z \sim 0.2$, with eccentricities as high as 0.9 when the signals enter the detector band. Even one confident detection of an eccentric black hole binary would give very strong evidence for the preferred formation channel of binary black holes (BBH). However, it has been shown that a large fraction of GW signals from binary coalescence with non-negligible eccentricities will be missed by the current template searches, since the quasi-circular waveform families employed in those searches are substantially suboptimal to detect GWs from compact binaries with eccentricities > 0.05. This is mainly due to the significant dephasing and the amplitude modulations that are expected to occur in eccentric GW signals. Third-generation ground-based detectors like the Einstein Telescope (ET) and space-based GW observatories like LISA will have much improved sensitivities in the low-frequency regime and are expected to observe stellar-mass BBH like GW150914 a significant time before merger, when eccentricity effects may be expected to be non-negligible. It has been estimated that LISA should resolve eccentricities $e_0 \geq 0.01$ and may even be able to detect 90% of binaries inspiraling along orbits with $e_0 \geq 0.001$. Therefore, it is highly desirable to incorporate effects of residual orbital eccentricity in the source modeling for data analysis with present and future generations of GW observatories.

As active member of the *Waveforms* working group of the LSC, we develop codes for the LIGO Algorithm Library (LAL) that provide ready-to-use, post-Newtonian (PN) accurate inspiral templates for compact binaries in inspiraling eccentric orbits, and develop the necessary data analysis tools that would enable the LSC to use these templates for the estimation of GW source parameters and eventually for GW searches.

M. Haney is working to improve previously developed time-domain and frequency-domain GW models of eccentric binary inspiral [1], with the aim of achieving templates with a PN accuracy that is comparable to that of the widely used quasi-circular inspiral approximants. With collaborators at UIB Palma, she has begun to study data analysis implications of a ready-to-use, 'effective eccentric variant' of the non-precessing IMRPhenomD waveform family, with the aim of including eccentricity as an integral part of the phenomenological modeling process. (Phenomenological frequency-domain waveform models have become standard tools for the GW data analysis of black-hole merger events with LIGO and Virgo.) This preliminary Phenom model for eccentric coalescence was developed and implemented for data analysis during LIGO's first observing run, restricted to non-spinning black holes and incorporating the effects of small orbital eccentricities during the inspiral regime. With the help of hybrid waveforms that include information from numerical relativity simulations of eccentric black-hole coalescence, she has started to explore the accuracy of the model over the parameter space and work towards improving the phenomenological modeling of the waveforms. The long-term goal of this project is the development of an accurate and computationally efficient frequency-domain inspiral-merger-ringdown (IMR) GW model for generic binaries with both eccentricity and spin precession. With collaborators at INFN Trento and Cardiff University, she is employing these models of compact binary coalescence with non-negligible eccentricity for a performance comparison of the modeled (circular template-based) and unmodeled (burst) pipelines of the LSC. Such a systematic study of the effects of eccentricity on GW searches will lead to a better understanding of certain search characteristics, such as estimates of sensitivity, upper limits on events rates, systematics of parameter estimation, estimation of the background. Y. Boetzel is working on a new, generic Fourier-domain inspiral model that combines effects of eccentricity and spin precession, which can prove to be a crucial tool to probe waveform systematics in GW source parameter estimation. A first publication is currently under review by Physical Review D, and a timely software implementation of these waveforms in the LIGO Algorithm Library (LAL) is ongoing. Other eccentricity-related projects for the LSC include work by M. Haney to explore the possibility of using parameterized tests of GR violations in GW data (with gIMR waveform models) to extract information about the eccentricity of a binary system, to study a possible connection between the inspiral coefficients in the gIMR analysis and plausible eccentricity effects. For the second part of his master thesis, Michael Ebersold studies the nonlinear memory effect of eccentric binary systems, extending work by Favata to the post-Newtonian regime. GW memory is a (as-of-yet unobserved) strong-field effect, i.e. a permanent displacement of spacetime arising from a non-oscillatory contribution to the GW polarizations due to an interaction of the GW with themselves. Although memory effects in the GW signal from an individual merger event have signal-to-noise ratios that are too small to be resolved by ground-based detectors, it has been shown that a cumulative stacking of signal-to-noise ratio from GW measurements of many binary black hole mergers can lead to a detection of GW memory in principle. With collaborators at INFN Trento, we are probing the prospects for detection of GW memory from a population of eccentric binary black hole mergers, with the potential to provide hints for the understanding of formation channels of black holes, even in the absence of an unambiguous detection of a black hole merger event with significant eccentricity.

Compact binaries in hyperbolic orbits are plausible GW sources for the currently available and upcoming GW observatories. Though compact binaries in hyperbolic orbits are expected to be rare GW events, close encounters of an unbound binary containing a neutron star may be associated with electromagnetic flares. This feature makes binaries on hyperbolic orbits interesting candidates for triggered GW burst searches. Additionally, there has been significant interest from within the LSC to explore hyperbolic waveform models in the context of a possible application in classifying sine-Gaussian glitches in GW detector data. For his master thesis, Oliver Fischer has calculated the radiated energy and power spectrum during a hyperbolic encounter, checking and correcting the results from [2]. With collaborators at TIFR Mumbai and Seoul National University, M. Haney has developed PN-accurate 'burst' templates for compact binaries in unbound orbits, by computing 3PN-accurate quasi-Keplerian parameterization and extending previous efforts in De Vittori et al. (2014) [2] to compute the orbital dynamics of hyperbolic binaries. A publication introducing this waveform model is currently under review by Physical Review D, with ongoing work towards an implementation of hyperbolic waveforms in the LAL software and an exploration of the data analysis implications of certain memory effects in the GW polarization states.

As part of the R&D efforts of the Testing GR working group of the LSC, M. Haney has developed a new data analysis infrastructure that generically tests for imprints of (GR violating) gravitational dipole radiation on GW signals from compact binary coalescence, and obtains constraints on certain specific mechanisms for the emission of dipole radiation. This pipeline has passed internal review by the LSC and has been used as a standard test of GR in GW data during the recent second observing run (O2) of Advanced LIGO. Efforts are ongoing to extend and improve the dipole radiation test by working towards including higher-order dipole radiation effects in GW phasing that are important at higher frequencies, particularly during the late inspiral and the merger.

Recently and prompted by the detection of GW170817 (see Fig. 3.2), M. Haney and collaborators at TIFR Mumbai have started to study effects of magnetic dipole-dipole interaction in binary neutron star mergers on the GW phasing of frequency-domain waveforms of such systems [3]. The aim of this project is a possible distinction of binary neutron stars (BNS) with magnetic dipole moments from neutron star - black hole sources, by studying the systematic bias on the chirp mass that is estimated from GW data.

M. Haney has also devoted a substantial amount of time to service work for the LSC. She has been running data analysis for the binary black hole and BNS events detected during LIGO-Virgo's second observing run, and is a member of the team that is tasked with writing the LSC-Virgo collaboration paper that will detail tests of GR for the neutron star merger GW170817. She has also served as an internal LSC reviewer for several publications and data analysis software. Crucially, she was involved in efforts to develop and review (for the data analysis of GW170817) accurate and efficient inspiral-merger-ringdown models for BNS mergers that augment binary black hole model with numerical-relativity-tuned tidal effects. A short author list publication on this work is currently under review by Physical Review D.

[1] S. Tanay, M. Haney, and A. Gopakumar,
Phys. Rev. D **93**, 064031 (2016)

[2] L. De Vittori, A. Gopakumar, A. Gupta, and Ph. Jetzer,
Phys. Rev. D **90** (2014) 124066

[3] K. Ioka, and K. Taniguchi,
Astrophys. J. **537**, 327–333 (2010)

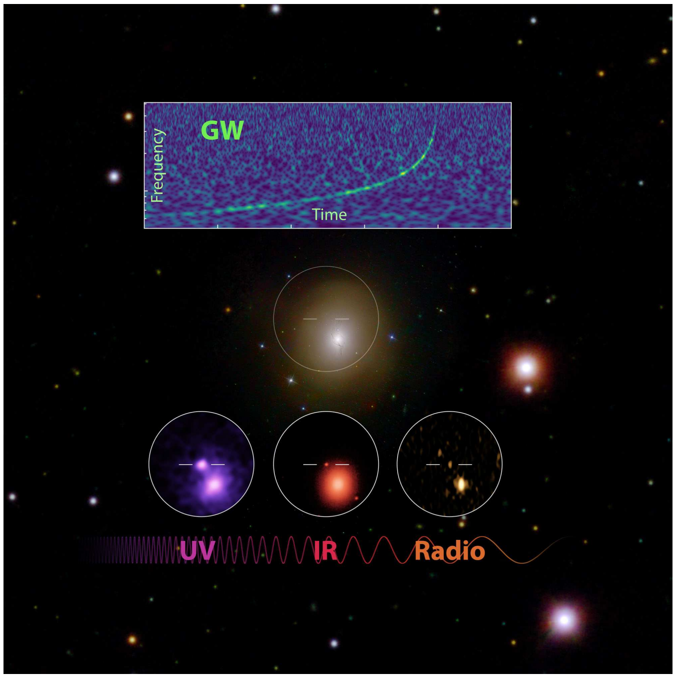

FIG. 3.2 – Detection of the GW170817 neutron star merger in gravitational waves (LIGO-Virgo) and electromagnetic radiation in ultra-violet (Swift satellite), infrared (Gemini-South Telescope) and radio (Very Large Array).
Copyright Robert Hurt (Caltech/IPAC), Mansi Kasliwal (Caltech), Gregg Hallinan (Caltech), Phil Evans (NASA) and the GROWTH collaboration .

3.2 Gravitational Lensing

The concepts of 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 – are too well known to need elaborating here. Nowadays, however, gravitational lensing is valued, more than as a test of GR, 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, P. Denzel 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.

3.3 Space clocks and relativity

Together with the academic guest Dr. Jianfeng Su, Qiang Wang and Qinghua Wang from Spectratime in Neuchâtel, we studied the possibility to detect GW by putting very accurate atomic clocks on satellites on particular orbits. The result of this investigation has been published in the journal Classical and Quantum Gravity [4].

Also using spacecraft clocks, we investigated the possibility of measuring frame dragging by planets in a paper which appeared in Frontiers in Astronomy and Space Science [5].

Together with Fupeng Zhang at Sun Yat-Sen University in Guangzhou, China, P. Saha continued studying the relativistic spacetime expected around the Galactic-center black hole with the help of natural clocks. In a paper in the Astrophysical Journal [6], they conclude that if (as expected) the next generation of radio telescopes finds a pulsar in close orbit around the black hole (comparable to known stars), the black-hole spin and its orientation could be measured.

[4] J. Su *et al.*, Class. Quantum Grav. **35**, 085010 (2018)

[5] A. Schärer *et al.*, Front. Astron. Space Sci. **4**, 11 (2017)

[6] F. Zhang, and P. Saha, Astrophys. J. **849**, 33 (2017)

3.3.1 ACES workshop

On 29 and 30 June 2017 we organized at the Irchel campus of University of Zürich the ACES workshop, the first of a series. ACES (Atomic Clock Ensemble in Space) is a space mission at whose heart is an ensemble of atomic clocks on board the international space station (ISS) and microwave and optical links to compare the onboard clocks to clocks on the ground. It features a cold atom clock (PHARAO) and a hydrogen maser, built in Switzerland, that will bring unprecedented accuracy into space, together with world-wide dissemination of its time-scale to ground clocks. The launch of ACES/PHARAO is expected for 2020. The science objectives are in fundamental physics, time/frequency metrology, cold-atom space physics, study of the ionosphere and geodesy. One of its primary goals is a measurement of the gravitational redshift, a central prediction of Einstein's GR and a fundamental constituent of the Einstein Equivalence Principle, the experimental foundation of all metric theories of gravitation. The workshop brought together the scientific community interested in the results of ACES/PHARAO in all domains, from theoretical physics to cold atoms and application in geodesy and atmospheric studies. It consisted of invited and contributed presentations on the details of ACES, data analysis and scientific applications. The aim of the workshop was to prepare the scientific community for the upcoming launch and scientific exploitation of the data.

3.4 Scalar-Tensor Theories

Scalar-tensor theories are a promising class of alternative theories of gravitation. They contain, in addition to the metric tensor of GR, a scalar degree of freedom. Upcoming precision experiments might detect violations of general relativity, which could be explained by such theories. Together with Manuel Hohmann from the University of Tartu, Estonia, Andreas Schärer investigated multi-scalar-tensor theories. These theories are a further generalization which contain multiple such scalar fields. The results have been published in Physical Review D [7].

Simone Bavera in his master thesis studied the role of the boundary terms which appear in the Einstein-Hilbert action.

[7] M. Hohmann, and A. Schärer,
Phys. Rev. D **96**, 104026 (2017)