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Cover illustration: Artist's impression (courtesy of Ceravolo Graphic Studio) of a double pulsar binary emitting both radio and gravitational waves during the spiral-in phase. The system is depicted against a background of the population of coalescing double neutron star binaries in the Galaxy.

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Preface

A very attractive feature of the theory of general relativity is that it is a perfect example of a "falsifiable" theory: no tunable parameter is present in the theory and therefore even a single experiment incompatible with a prediction of the theory would immediately lead to its inevitable rejection, at least in the physical regime of application of the aforementioned experiment. This fact provides additional scientific value to one of the boldest and most fascinating achievements of the human intellect ever, and motivates a wealth of efforts in designing and implementing tests aimed at the falsification of the theory.

The first historical test on the theory has been the deflection of light grazing the solar surface (Eddington 1919): the compatibility of the theory with this first experiment together with its ability to explain the magnitude of the perihelion advance of Mercury contributed strongly to boost acceptance and worldwide knowledge. However, technological limitations prevented physicists from setting up more constraining tests for several decades after the formulation of the theory. In fact, a relevant problem with experimental general relativity is that the predicted deviations from the Newtonian theory of gravity are very small when the experiments are carried out in terrestrial laboratories. A rough estimate of the expected magnitude of general relativity corrections can be drawn from a comparison between the classical gravitational potential energy $E_{\rm grav} \sim -GM^2/R$ of a body of mass M and radius R and the rest mass energy of the same body, $E_{\rm rest} = Mc^2$ (G being the gravitational constant and c the speed of light in vacuum). On Earth, the dimensionless ratio $\epsilon = |E_{\rm grav}/E_{\rm rest}|$ is of only $\sim 10^{-10}$ and, as a consequence, very sensitive experimental apparatuses are necessary for detecting the tiny discrepancies resulting from the application of Einstein's theory with respect to the predictions of Newtonian gravity.

After the pioneering experimental era, general relativity tests have reflourished only in the last fifty years, when new generation devices (such as radar and lasers) and the birth of astronautics allowed us to design and carry out much more accurate experiments in space, such as the use of radar technology (Shapiro 1964) for transmitting pulses towards either Venus or Mercury, and for measuring the time delay of the echoes. According to general relativity these delays are enhanced when the pulses pass close to the Sun. Laser ranging to the Moon (Nordtvedt 1968) was used to set upper limits to the amplitude of the lunar orbit oscillations that are expected to occur if the ratio of the gravitational to inertial mass of the Earth differs from the value (equal to unity) predicted by general relativity. More recently, the frequency shift of radio photons to and from the Cassini spacecraft as they pass near the Sun has been measured (Bertotti 2003) probing the degree to which photons are deflected and delayed by the curvature of space-time produced by the Sun. The last big step forward in the field has been the launch of the Relativity Gyroscope Experiment (Gravity Probe B) which collected data orbiting the Earth between 2004 an 2005 (Everitt 2007). The aim was to investigate two well known predictions of general relativity : (i) the occurrence of the geodetic precession effect (resulting from the warp of the local space-time due to the mass of the Earth) and, even more ambitiously, the frame dragging effect (also known as gravitomagnetism), generated by the rotation of Earth, which drags and twists the space-time surrounding it. Final data release of this experiment is expected during 2008, although some preliminary announcements about the measurement of the geodetic effect have already been reported.

All the general relativity tests listed above involve celestial bodies of the solar system, among which the highest value of ϵ is that of the Sun, having $\epsilon \sim 10^{-6}$. Therefore, those tests belong to the class of experiments that investigate the so-called *weak-field limit* of gravitational physics, i.e. a regime where the velocities of the bodies imposed by the gravitational field are small compared to c and the energy associated with the gravitational field of the bodies is a tiny fraction of their rest mass energy. The amazing outcome of a century of experimental physics is that general relativity has been passing all the aforementioned tests – as well as all the others of the same class – with full marks and *cum laude*.

Thus, why bother with further investigations? On the epistemological side, no physical theory can ever be proved, but only falsified; hence, the request for more and more refined experiments can never find an end. However, in the particular case of general relativity, there are still fundamental and unanswered problems urging an extension of the range of tests. At present, the main goal of theoretical physics is to describe all the phenomena in Nature in terms of a unified theory, which should encompass gravity, nuclear and electroweak interactions in a single framework. A knotty step toward this unified model is to combine the classical and deterministic (although often very difficult to calculate) predictions of general relativity with the probabilistic approach of quantum mechanics. Many decades of unsatisfactory conclusions in the field of quantum gravity may be an indication that some of the ingredients in current attempts are not suitable for constructing the desired Grand Unification Theory. In particular, one may wonder whether general relativity – very successful in the condition of *weak-field* gravity – remains the best available theory for describing Nature under extreme physical conditions, such as those holding in the regime where a unified model applies.

In the presence of gravitational effects alone, the notion of extreme physical conditions can be reworded stating that the dimensionless parameter ϵ tends to unity. This is the so-called *strong-field* realm of gravity theories (e.g. Will 2001): it applies for instance to the intense gravitational fields associated with the Planck-scale, at which a quantum formulation of general relativity is unavoidable, or to the nearness of a collapsed object, like the event horizon of a static black hole ($\epsilon \sim 0.5$) or the surface of a neutron star ($\epsilon \sim 0.2$). Under these conditions, general relativity could finally show its limits of applicability, being supplanted by alternative theories of gravity, either already proposed or still to be elaborated. In this perspective, considering the ambitious aims of the physics of the XXI century, it is mandatory to establish the most stringent limits on the falsifiability of the Einsteinian theory in the *strong-field* regime.

How to perform that task? It is really hard to conceive the possibility of testing the *strong-field* regime in a terrestrial laboratory or in the solar system. As a consequence, we have to search for natural laboratories in the Cosmos: in this context, *relativistic objects* hosted in *compact binaries* offer magnificent opportunities.

The term *relativistic objects* refers mostly to black holes and neutron stars, while *compact binaries* to binaries where gravitational wave inspiral influences binary evolution within a Hubble time. When binaries hosting two collapsed stars are in their latest stage of coalescence – driven by gravitational radiation damping – the typical orbital velocity approaches c and the orbital separation becomes of the order of their size, implying that the physical processes occur in the typical *strong-field* regime. Various types of spiralling compact binaries are expected to result from stellar binary evolution: double neutron stars, neutron star plus black hole systems and double black hole systems. These binaries are the most promising targets for the current generation of ground-based interferometers for the detection of gravitational waves, like LIGO and VIRGO. Much more massive binary black hole systems should also develop from cosmological mergers of galaxies and their inspiral is the main objective of LISA, the future space-based gravitational wave interferometer. Direct detection of the gravitational waves released during these inspirals would be an enormous step forward for experimental gravity and a wonderful support to the 100 year old predictions of general relativity. At the same time, these investigations have the potentiality of discovering the existence of limits to the applicability of Einstein's theory, e.g. if a dipole gravitational radiation contribution – null in general relativity, but predicted in the class of the so called scalar-tensor theories – should enter the formulae describing the effects of radiation back-reaction on orbit phasing. Ruinous consequences for general relativity would also derive for example from the detection of more than two transverse modes of propagation of the waves.

Taken at face value, the earlier stages of evolution of close binaries – well before coalescence – may not satisfy the conditions for a *strong-field* regime. In fact, when the orbital separation is large, any binary component moves in the weak gravitational field of the companion and thus $\epsilon \ll 1$. However, in most alternative theories of gravity – e.g. for example the scalar-tensor theories mentioned above – the motion and the gravitational radiation damping depend on the gravitational binding energy of the involved bodies. Since in compact objects, like neutron stars, the gravitational binding energy is very large (i.e. ϵ is close to unity), significant deviations from the orbital motion are expected to be detectable even in the weak field limit. In this framework, a particularly interesting case of study is that of *binary pulsars*, that is binary systems comprising a neutron star which emits collimated beams of radio waves, observed as pulses, once per rotation of the neutron star. Due to evolutionary reasons, the pulsars included in binary systems with other compact objects very often behave as *highly stable clocks* . The measurement of the times of arrival of their pulses allows for an accurate determination of their orbital motion. This provides the observational basis for the search for deviations from the general relativity predictions and, in summary, for using the binary pulsars as a magnificent laboratory for the *strong-field* tests of Einstein's theory.

Distant cosmic laboratories compared to terrestrial or space-based laboratories require a deep understanding of the experimental procedures adopted in astrophysics, for which we are only *passive* observers. In these laboratories we have no opportunity to alter the conditions of the apparatus, nor to selectively modify the experimental parameters in order to highlight and better study the various physical effects contributing to the process under analysis. In the case of astrophysics, all the information must be extracted only from the flow of particles (in the form of photons, gravitons, etc.) supplied, at a non-tunable level, by the cosmic laboratory. In light of that, a first relevant issue is to maximize the number and the usefulness of the collected particles, i.e. to make the detectors and the data analysis as efficient as possible. Selection of the most suitable natural laboratories is another key point, as well as the understanding of how the history and the properties of their constituents can affect the interpretation of the data. In this respect, it is very important to know the origin and the evolutionary path that led to the formation of any natural laboratory, its basic physical features and its cosmic environment.

This book, entitled *Physics of relativistic objects in compact binaries: from birth to coalescence*, has been conceived and assembled with the aim of providing a comprehensive and updated report on the astrophysical approach to the investigation of gravity theories, with particular attention to *strong-field* tests of general relativity and alternate theories, performed using collapsed objects in relativistic binaries as laboratories. The text collects reviews written by scientists at the front-line of this investigation and known worldwide for their major and often still unsurpassed contributions in this field. The book covers various topics, which are reviewed both on the observational and the theoretical side: (i) from binaries as test-beds of gravity theories to binary pulsars as cosmic laboratories, (ii) from binary stars evolution to the formation of relativistic binaries, (iii) from short gamma-ray bursts to low mass X-ray binaries, (iv) from stellar-mass black hole binaries to coalescing super-massive black holes in galaxy mergers.

In particular, the first chapter reviews gravity theories describing the motion of point masses in a binary. The physics presented and the mathematical tools introduced set the basis for a correct and unambiguous interpretation of the large data set provided by the observation of binary pulsars. The procedure of timing this class of pulsars, as well as some of the most remarkable applications of that, are described in detail in Chapter 2, whereas Chapter 3 deals with the concepts driving the experiments which search for additional relativistic binary pulsars.

The following five chapters introduce the reader to the realm of binaries hosting one or two relativistic objects, as observed and interpreted in an astrophysical context. Chapter 4, reviews the critical channels of formation of compact binaries in the galactic field, highlighting the chief steps that signal their formation and evolution. Theory and observations are inter-winded in this chapter, designed to give a rather complete view of the complex phenomenology of neutron stars and black holes in binaries and of the physical tools used for the interpretation and description of these sources. Chapter 5 continues in this study, exploring the formation of binary pulsars, and more generally of binaries with two compact stars – either a neutron star or a black hole, also of intermediate mass – in the dense collisional environment of a globular cluster, where they form preferentially via close gravitational encounters. Short gamma-ray burst sources are the subject of Chapter 6: in the context of this book, they can be viewed as the counterparts of the inspiral and merger of neutron star-black hole or double neutron star binaries. The chapter reviews the impact that short gamma-ray burst sources have on our knowledge of the most energetic events in the universe. Chapter 7 continues by surveying a number of powerful diagnostic tools used to explore and map space-time in the vicinity of accreting neutron stars or black holes in low mass X-ray binary systems. Chapter 8 introduces the reader to a class of systems, the white dwarfs in ultra-compact binaries, that are currently receiving attention, being important sources of low frequency gravitational waves, and so potential systems for testing general relativity.

The book ends with a chapter dedicated to gravitational waves from coalescing black holes, from the perspective that their detection will open a new window into our universe. The recent remarkable advances in numerical relativity in describing the coalescence of black holes have motivated the introduction of this chapter. In particular, Chapter 9 describes again the two body problem and how it is solved in numerical relativity. Focused mainly on massive binary black holes, this chapter reports on the latest achievements in the study of the dynamics of the merger in full general relativity and their impact on physics, astronomy, and cosmology.

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Binary Systems as Test-Beds of Gravity Theories

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1 Introduction

The discovery of binary pulsars in 1974 [1] opened up a new testing ground for relativistic gravity. Before this discovery, the only available testing ground for relativistic gravity was the solar system. As Einstein's theory of General Relativity (GR) is one of the basic pillars of modern science, it deserves to be tested, with the highest possible accuracy, in all its aspects. In the solar system, the gravitational field is slowly varying and represents only a very small deformation of a flat spacetime. As a consequence, solar system tests can only probe the quasi-stationary (non-radiative) *weak-field* limit of relativistic gravity. By contrast binary systems containing compact objects (neutron stars or black holes) involve spacetime domains (inside and near the compact objects) where *the gravitational field is strong*. Indeed, the surface relativistic gravitational field $h_{00} \simeq 2\,GM/c^2R$ of a neutron star is of order 0.4, which is close to the one of a black hole ($2\,GM/c^2R = 1$) and much larger than the surface gravitational fields of solar system bodies: $(2\,GM/c^2R)_{\rm Sun} \sim 10^{-6}$, $(2\,GM/c^2R)_{\rm Earth} \sim 10^{-9}$. In addition, the high stability of "pulsar clocks" has made it possible to monitor the dynamics of its orbital motion down to a precision allowing one to measure the small ($\sim (v/c)^5$) orbital effects linked to the propagation of the gravitational field at the velocity of light between the pulsar and its companion.

The recent discovery of the remarkable *double* binary pulsar PSR J0737−3039 [2, 3] (see also the contributions by M. Kramer and by N. D'Amico and M. Burgay to this volume) has renewed the interest in the use of binary pulsars as test-beds of gravity theories. The aim of this chapter is to provide an introduction to the theoretical frameworks needed for interpreting binary pulsar data as tests of GR and alternative gravity theories.