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Relativity and Gravitation

100 Years After Einstein in Prague

Springer

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Introduction The texts based on 25 plenary talks from 32 given are included in the Volume "General, Relativity, Cosmology and Astrophysics: 100 Years After Einstein in Prague" (editors J. B. and T. L.), Springer Verlag 2013. In order to give a more complete picture of the whole conference, the abstracts of the 25 plenary talks are included in the first chapter of these Proceedings.

Part I Gravity and Prague

Kepler and Mach's Principle

Julian Barbour

The definitive ideas that led to the creation of general relativity crystallized in Einstein's thinking during 1912 while he was in Prague. At the centenary meeting held there to mark the breakthrough, I was asked to talk about earlier great work of relevance to dynamics done at Prague, above all by Kepler and Mach. The main topics covered in this paper are: some little known but basic facts about the planetary motions; the conceptual framework and most important discoveries of Ptolemy and Copernicus; the complete change of concepts that Kepler introduced and their role in his discoveries; the significance of them in Newton's work; Mach's realization that Kepler's conceptual revolution needed further development to free Newton's conceptual world of the last vestiges of the purely geometrical Ptolemaic world view; and the precise formulation of Mach's principle required to place GR correctly in the line of conceptual and technical evolution that began with the ancient Greek astronomers.

Einstein in Prague: Relativity Then and Now

Jiří Bičák

It was during his stay in Prague that Einstein started in earnest to develop his ideas about general relativity. I will recall those days in 1911 and 1912, discuss

Einstein's papers on gravitation from that period, and emphasize which new concepts and ideas he introduced. I also want to indicate how the main themes that preoccupied him then, the principle of equivalence, bending of light, gravitational redshift, and frame dragging effects, are alive in contemporary relativity.

Part II Classical General Relativity

Observers, Observables and Measurements in General Relativity

Donato Bini

To perform any physical measurement it is necessary to identify in a nonambiguous way both the observer and the observable. A given observable can be then the target of different observers: a suitable algorithm to compare among their measurements should necessarily be developed, either formally or operationally. This is the task of what we call "theory of measurement," which we discuss here in the framework of general relativity.

Some Links Between General Relativity and Other Parts of Physics

Gary W. Gibbons

Now that General Relativity has become such a central part of modern physics, its geometrical formalism being taught as part of almost all undergraduate physics courses, it is natural to ask: how can its basic concepts and techniques be used to illuminate areas of physics which have no connection with gravity? Another way of asking this question is: are the situations analogous to those occurring in General Relativity? The search for such analogs is of course an old one, but recently, because of advances in technology, these questions have become more topical. In this talk I will illustrate this theme by examples drawn from optics, acoustics, liquid crystals, graphene, and the currently popular topic of cloaking.

The General Relativistic Two Body Problem and the Effective One Body Formalism

Thibault Damour

A new analytical approach to the motion and radiation of (comparable mass) binary systems was introduced in 1999 under the name of Effective One-Body (EOB) formalism. We review the basic elements of this formalism, and discuss some of its recent developments. Several recent comparisons between EOB predictions and Numerical Relativity (NR) simulations have shown the aptitude of the EOB formalism to provide accurate descriptions of the dynamics and radiation of various binary systems (comprising black holes or neutron stars) in regimes that are inaccessible to other analytical approaches (such as the last orbits and the merger of comparable mass black holes). In synergy with NR simulations, post-Newtonian (PN) theory and Gravitational Self-Force (GSF) computations, the EOB formalism is likely to provide an efficient way of computing the very many accurate template waveforms that are needed for Gravitational Wave (GW) data analysis purposes.

Gravitational Self-Force: Orbital Mechanics Beyond Geodesic Motion

Leor Barack

The question of motion in a gravitationally bound two-body system is a long-standing open problem of General Relativity. When the mass ratio η is small, the problem lends itself to a perturbative treatment, wherein corrections to the geodesic motion of the smaller object (due to radiation reaction, internal structure, etc.) are accounted for order by order in η, using the language of an effective *gravitational self-force*. The prospect for observing gravitational waves from compact objects inspiralling into massive black holes in the foreseeable future has in the past 15 years motivated a program to obtain a rigorous formulation of the self-force and compute it for astrophysically interesting systems. I will give a brief survey of this activity and its achievements so far, and will identify the challenges that lie ahead. As concrete examples, I will discuss recent calculations of certain conservative post-geodesic effects of the self-force, including the $O(\eta)$ to the precession rate of the periastron. I will highlight the way in which such calculations allow us to make fruitful contact with other approaches to the two-body problem.

Hamiltonian Formalism for Spinning Black Holes in General Relativity

Gerhard Schäfer

A Hamiltonian treatment of gravitationally interacting spinning black holes is presented based on a tetrad generalization of the Arnowitt-Deser-Misner (ADM) canonical formalism of general relativity. The formalism is valid through linear order in single spins. For binary systems, higher order post-Newtonian Hamiltonians are given in explicit analytic forms. A next-to-leading order in spin generalization is presented, others are mentioned. Comparisons between the Hamiltonian formalisms by ADM, Dirac, and Schwinger are made.

Stability of Marginally Outer Trapped Surfaces and Geometric Inequalities

Marc Mars

Marginally outer trapped surfaces (MOTS) admit a notion of stability that in many respects generalizes a similar notion for minimal hypersurfaces. Stable MOTS play an interesting role in a number of geometric inequalities involving physical parameters such as area, mass, charge or, in the axially symmetric case, angular momentum. Some of those inequalities are global in nature while others are local, with interesting relationships between them. In this lecture the notion of stable MOTS will be reviewed and some of the geometric inequalities involving stable MOTS will be described.

Stationary Black-Hole Binaries: A Non-existence Proof

Gernot Neugebauer and Jörg Hennig

We resume former discussions of the question of whether the spin–spin repulsion and the gravitational attraction of two aligned black holes can balance each other. Based on the solution of a boundary problem for disconnected (Killing) horizons and the resulting violation of characteristic black hole properties, we present a nonexistence proof for the equilibrium configuration in question. From a mathematical point of view, this result is a further example of the efficiency of the inverse ("scattering") method in nonlinear theories.

Dynamic and Thermodynamic Stability of Black Holes and Black Branes

Robert M. Wald

I describe recent work with Stefan Hollands that establishes a new criterion for the dynamical stability of black holes in $D \geq 4$ spacetime dimensions in general relativity with respect to axisymmetric perturbations: Dynamical stability is equivalent to the positivity of the canonical energy, $\mathscr{E}$, on a subspace of linearized solutions that have vanishing linearized ADM mass, momentum, and angular momentum at infinity and satisfy certain gauge conditions at the horizon. We further show that $\mathscr{E}$ is related to the second order variations of mass, angular momentum, and horizon area by $\mathscr{E} = \delta^2 M - \sum_i \Omega_i \delta^2 J_i - (\kappa/8\pi)\delta^2 A$, thereby establishing a close connection between dynamical stability and thermodynamic stability. Thermodynamic instability of a family of black holes need not imply dynamical instability because the perturbations towards other members of the family will not, in general, have vanishing linearized ADM mass and/or angular momentum. However, we prove that all black branes corresponding to thermodynmically unstable black holes are dynamically unstable, as conjectured by

Gubser and Mitra. We also prove that positivity of $\mathscr{E}$ is equivalent to the satisfaction of a “local Penrose inequality,” thus showing that satisfaction of this local Penrose inequality is necessary and sufficient for dynamical stability.

Instability of Anti-de Sitter Spacetime

Piotr Bizoń and Andrzej Rostworowski

In this talk we summarize our recent numerical and perturbative calculations which indicate that AdS spacetime is unstable. Namely, we study spherically symmetric Einstein-massless-scalar field equations with negative cosmological constant and show that this system is unstable against black hole formation for a large class of initial data arbitrarily close to the AdS solution. We conjecture that this instability is triggered by a resonant mode mixing which gives rise to diffusion of energy from low to high frequencies.

Higher-Dimensional Black Holes

Harvey S. Reall

This article reviews black hole solutions of higher dimensional General Relativity. The focus is on stationary vacuum solutions and recent work on instabilities of such solutions.

Black Holes, Hidden Symmetry and Complete Integrability: Brief Review

Valeri P. Frolov

This paper contains a brief review of the remarkable properties of higher dimensional rotating black holes with the spherical topology of the horizon. We demonstrate that these properties are connected with and generated by a special geometrical object, the Principal Conformal Killing-Yano tensor (PCKYT). The most general solution, describing such black holes, Kerr-NUT-ADS metric, admits this structure. Moreover, a solution of the Einstein Equations with (or without) a cosmological constant which possesses PCKYT is the Kerr-NUT-ADS metric. This object (PCKYT) is responsible for such remarkable properties of higher dimensional rotating black holes as: (i) complete integrability of geodesic equations and (ii) complete separation of variables of the important field equations.

Part III Cosmology and Quantum Gravity

Cosmological Models and Stability

Lars Andersson

Principles in the form of heuristic guidelines or generally accepted dogma play an important role in the development of physical theories. In particular, philosophical considerations and principles figure prominently in the work of Albert Einstein. As mentioned in the talk by Jiří Bičák at this conference, Einstein formulated the equivalence principle, an essential step on the road to general relativity, during his time in Prague 1911–1912. In this talk, I would like to discuss some aspects of cosmological models. As cosmology is an area of physics where "principles" such as the "cosmological principle" or the "Copernican principle" play a prominent role in motivating the class of models which form part of the current standard model, I will start by comparing the role of the equivalence principle to that of the principles used in cosmology. I will then briefly describe the standard model of cosmology to give a perspective on some mathematical problems and conjectures on cosmological models, which are discussed in the later part of this paper.

Inflation and Birth of Cosmological Perturbations

Misao Sasaki

We review recent developments in the theory of inflation and cosmological perturbations produced from inflation. After a brief introduction of the standard, single-field slow-roll inflation, and the curvature and tensor perturbations produced from it, we discuss possible sources of nonlinear, non-Gaussian perturbations in other models of inflation. Then we describe the so-called δN formalism, which is a powerful tool for evaluating nonlinear curvature perturbations on super Hubble scales.

Loop Quantum Gravity and The Planck Regime of Cosmology

Abhay Ashtekar

The very early universe provides the best arena we currently have to test quantum gravity theories. The success of the inflationary paradigm in accounting for the observed inhomogeneities in the cosmic microwave background already illustrates this point to a certain extent because the paradigm is based on quantum field theory on the curved cosmological space-times. However, this analysis excludes the Planck era because the background space-time satisfies Einstein's equations all the way back to the big bang singularity. Using techniques from loop quantum gravity, the paradigm has now been extended to a self-consistent theory from the Planck regime to the onset of inflation, covering some 11 orders of magnitude in curvature. In addition, for a narrow window of initial conditions, there are departures from the standard paradigm, with novel effects, such as a modification of the consistency relation involving the scalar and tensor power spectra and a new source for non-Gaussianities. The genesis of the large-scale structure of the universe can be traced back to quantum gravity fluctuations in the Planck regime. This report provides a bird's eye view of these developments for the general relativity community.

The Inflationary Origin of the Seeds of Cosmic Structure: Quantum Theory and the Need for Novel Physics

Daniel Sudarsky

The Inflationary account for the emerging of the seeds of cosmic structure from quantum fluctuations is a central part of our current views of cosmology. It is, on the one hand, extremely successful at the phenomenological level, and yet it retains an aspect that is generally regarded as controversial: The exact mechanism by which quantum fluctuations transmute into actual inhomogeneities. We will review the considerations that lead us to conclude that the fully satisfactory resolution of the issue requires novel physics and we will discuss an option we have been considering in this regard.

Quantum Gravity: The View From Particle Physics

Hermann Nicolai

This lecture reviews aspects of and prospects for progress towards a theory of quantum gravity from a particle physics perspective, also paying attention to recent findings of the LHC experiments at CERN.

Part IV Numerical Relativity and Relativistic Astrophysics

Three Little Pieces for Computer and Relativity

Luciano Rezzolla

Numerical relativity has made big strides over the last decade. A number of problems that have plagued the field for years have now been mostly solved. This progress has transformed numerical relativity into a powerful tool to explore fundamental problems in physics and astrophysics, and I present here three representative examples. These "three little pieces" reflect a personal choice and describe work that I am particularly familiar with. However, many more examples could be made.

Instabilities of Relativistic Stars

John L. Friedman and Nikolaos Stergioulas

Stable relativistic stars in uniform rotation forma two-parameter family, parametrized by mass and angular velocity. Limits on each of these quantities are associated with relativistic instabilities. A radial instability to gravitational collapse or explosion sets upper and lower limits on their mass, and an instability driven by gravitational waves may set an upper limit on their spin. Our summary of relativistic stability theory given here is based on and includes excerpts from the book *Rotating Relativistic Stars*, by the present authors.

Gravity Talks: Observing the Universe with Gravitational Waves

Bernard F Schutz

When the current upgrade of the large ground-based gravitational wave detectors LIGO and VIRGO is completed, the new science of gravitational wave astronomy will begin. In this overview I review the current status of the detector projects on the ground and in space (LISA), the kinds of signals and sources they expect to observe, and the science returns that are anticipated.

LISA in 2012 and Beyond: 20 Years After the First Proposal

Gerhard Heinzel and Karsten Danzmann

After 20 years of study as a joint ESA-NASA mission, LISA had to be redesigned as an ESA-only mission in 2011/2012 to meet programmatic and budgetary constraints of the space agencies. The result is a mission concept called “eLISA” or “NGO” with two arms instead of three and 1 million km armlengths instead of 5, which results in smaller launch mass but still provides revolutionary science. Nevertheless, even the reduced science is expected to be revolutionary for the study of black holes and other astrophysical and cosmological questions. “eLISA”/“NGO” was not selected in ESA’s call for the first (“L1”) large mission in the Cosmic Vision program, but is a strong candidate for the L2 call, with possible international contributions from the US and/or China.

Einstein’s Gravity as Seen by a Cosmic Lighthouse Keeper

Michael Kramer

The last years have seen continuing activities in the exploration of our understanding of gravity, motivated by results from precision cosmology and new precision astrophysical experiments. At the center of attention lies the question as to whether general relativity is the correct theory of gravity. In answering this question, we work not only towards correctly interpreting the phenomenon of "dark energy" but also towards the goal of achieving a quantum theory of gravity. In these efforts, the observations of pulsars, especially those in binary systems, play an important role. Pulsars do not only provide the only evidence for the existence of gravitational waves so far, but they also provide precision tests of general relativity and alternative theories of gravity. This talk summarizes the current state of art in these experiments and looks into the future.

The Astrophysical Signatures of Black Holes: The Horizon, The ISCO, The Ergosphere and The Light Circle

Marek A. Abramowicz

Three advanced instruments planned for a near future (LOFT, GRAVITY, THE EVENT HORIZON TELESCOPE) provide unprecedented angular and time resolutions, which allow to probe regions in the immediate vicinity of black holes. We may soon be able to search for the signatures of the superstrong gravity that is characteristic of black holes: the event horizon, the ergosphere, the innermost stable circular orbit (ISCO), and the photon circle. This review discusses a few fundamental problems concerning these theoretical concepts.

Energy Extraction from Spinning Black Holes Via Relativistic Jets

Ramesh Narayan, Jeffrey E. McClintock and Alexander Tchekhovskoy

It has for long been an article of faith among astrophysicists that black hole spin energy is responsible for powering the relativistic jets seen in accreting black holes. Two recent advances have strengthened the case. First, numerical general relativistic magnetohydrodynamic simulations of accreting spinning black holes show that relativistic jets form spontaneously. In at least some cases, there is unambiguous evidence that much of the jet energy comes from the black hole, not the disk. Second, spin parameters of a number of accreting stellar-mass black holes have been measured. For ballistic jets from these systems, it is found that the radio luminosity of the jet correlates with the spin of the black hole. This suggests a causal relationship between black hole spin and jet power, presumably due to a generalized Penrose process.