The Path to the Solution of the Relativistic Two-Body Problem, and Its Impact in Observing Gravitational Waves from Compact Binary Systems

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Background Information

In the last 30 years, the path to the analytical and numerical solution of the relativistic two- body problem in General Relativity, including the prediction of gravitational waveforms, has been closely intertwined with the construction of the gravitational-wave detectors LIGO and Virgo and the development of observational searches for binary systems composed of black holes and/or neutron stars. At times, this history has been marked by skepticism, failures, and successes reflecting different scientific research styles, in the US and Europe in particular.

More specifically,[1] between 1980 and 1992 important theoretical foundations in gravitational radiation and post-Newtonian theory[2] were carried out by a number of researchers. However, during those years, the analytical work on the two-body problem was considered mostly academic. It was not clear how relevant it would be to push calculations beyond the quadrupole formula for the direct observation of gravitational waves with ground-based detectors. The first important turning point was in 1993 when the importance of computing the gravitational-wave phasing beyond the leading order was pointed out.[3] Many crucial developments took place in the subsequent years. The second important turning point, which brought theory and observations closer, occurred in the mid- and late 1990s when the construction of LIGO in the US, Virgo in Italy, GEO600 in Germany, and TAMA300 in Japan started. The third turning point happened in the late 1990s and early 2000s when, pressed by the construction of gravitational-wave interferometers, the analytical effective- one-body approach[4] made a bold prediction for the late inspiral, merger, and ringdown waveform emitted by comparable-mass binary black holes. The effective-one-body formalism builds on post-Newtonian and black-hole perturbation theory results, and it is guided by the notion that non-perturbative effects can be captured analytically if the key ingredients that enter the two-body dynamics and gravitational-wave emission are properly resummed about the (exact) test-body limit results. Moreover, in the early 2000s, a pragmatic, numerical and analytical hybrid approach aimed at predicting the plunge and merger waveform was bravely carried out. This approach, called the Lazarus project,[5] consisted of evolving the binary system in full numerical relativity for less than an orbit just prior to merger before stopping the evolution, extracting the spacetime metric from the results of the simulation of a deformed black hole, and using perturbation theory calculations to complete the evolution during ringdown. The fourth relevant turning point occurred in 2005, when after more than thirty years of attempts, the first numerical-relativity simulations of binary black holes at last unveiled the merger waveform.[6] In the last 15 years, synergies and interplays between different analytical and numerical techniques to solve the two-body problem in General Relativity have grown considerably. A few paradigms were broken, in particular the nature of the binary black hole merger waveform, which turned out to be much simpler than what most people had expected or predicted. The last 15 years have also seen remarkable interactions between gravitational-wave data analysts, astrophysicists, and theorists to construct templates and search for signals with LIGO and Virgo detectors. This work culminated in the first detection of gravitational waves from merging black holes in 2015,[7] and continues to make analytical relativity a crucial research area for experiments that are revolutionizing our exploration of the Universe.

Given the above, Bonanno puts forward a project investigating this history in collaboration with the Max Planck Institute for the History of Science in Berlin, notably with Director Prof. Jürgen Renn, Independent Max Planck Research Group Leader Dr. Alexander Blum, and Prof. Dennis Lehmkuhl, Lichtenberg Professor of History and Philosophy of Physics at the University of Bonn. In particular, the project will focus on the history of the solution of the two-body problem in General Relativity in the last 30 years, with particular emphasis on the approximated analytical solutions, the interface with numerical relativity, and the role that the analytical- and numerical-relativity methods played in the discovery of gravitational waves with the LIGO and Virgo detectors in 2015. This research would close a crucial gap in the literature on the history of the relativistic two-body problem, as the latter has thus far (in the works of Peter Havas[8], Daniel Kennefick[9] and Dennis Lehmkuhl[10]) focused entirely on the work by Einstein and Grommer in the late 1920s, and on the work by Einstein, Infeld, and Hoffmann in the 1930s.[11] However, many of the questions posed by Einstein and his collaborators have only been answered in the past 30 years, while other questions and concepts posed by Einstein have been made more precise. Nevertheless, others still remain unanswered. The community of gravitational physicists that has worked on the solution of the relativistic two-body problem in these last 30 years and the community of historians and philosophers of science that has worked on Einstein and his collaborators have thus far not interacted with each other extensively. The proposed Balzan project would be pioneering in that it would bring Einstein scholars together with those that have succeeded him in working and solving the problem of motion in General Relativity for binary systems composed of black holes and/or neutron stars. Furthermore, the project would also contribute to recent debates in the history and philosophy of science concerning the changing role of approximation methods in modern physics[12] and their relation to numerical calculations and simulations.[13]

Description of the Project

The Balzan Prize money will be used to support:

i) one Balzan Fellow (PhD student) for three years;

ii) one or two Balzan Workshops that will also involve young scholars and foster interactions and discussions among historians and philosophers of science and gravitational physicists working on the relativistic two-body problem;

iii) a Balzan Visitor Program involving senior and younger scientists and aimed at creating an oral history collection on the subject. Young scientists at the AEI will also take advantage of interacting with the Balzan Visitors, who will be asked to give a Balzan Colloquium during their visit. The Balzan Colloquia will be recorded, and the recordings will be posted on the website of the Balzan project.

Prof. Thibault Damour, co-recipient of the Balzan Prize, will be involved in the above activities since he is a key historical figure who has worked in the field of the relativistic two-body problem during the last 50 years. The Balzan Fellow will visit IHES to collect information for the project. As part of the Balzan Visitor program, Damour has also been invited to visit the AEI to give a Balzan Colloquium.

The Balzan Fellowship will be advertised worldwide through the hyperspace mailing list which most gravitational physicists subscribe to, as well as the *Taking up Spacetime* blog and the *Phil Jobs* website, which play a similar role for historians and philosophers of science. The Balzan Fellow will be located at the Max Planck Institute for Gravitational Physics in Potsdam, which is 20 to 30 km away from Berlin, but the PhD student who is awarded the fellowship will have the opportunity to make regular visits the Max Planck Institute for History of Science in Berlin, and the University of Bonn. Two workshops are envisioned at the beginning and at the end of the Balzan project. The results of the proposed research will be published in international, leading peer-reviewed journals. A webpage dedicated to the Balzan project will be created and maintained on the AEI webpage.

[1] Here I follow Sec. 6.2 of A. Buonanno and B. Sathyaprakash, "Sources of Gravitational Waves: Theory and Observations," Chapter 6 in *General Relativity and Gravitation: A Centennial Perspective*, edited by A. Ashtekar, B.K. Berger, J. Isenberg, and M. MacCallum (2015).

[2] See, e.g., L. Blanchet, Living Review in Relativity 2 (2014) and references therein.

[3] C. Cutler et al. Phys. Rev. Lett. 70, 2984 (1993).

[4] A. Buonanno and T. Damour, Phys. Rev. D 59, 084006 (1999); Phys. Rev. D 62, 064015 (2000).

[5] J. Baker et al., Phys. Rev. Lett. 87, 121103 (2001).

[6] F. Pretorius, Phys. Rev. Lett. 87, 121101 (2005); M. Campanelli et al., Phys. Rev. Lett. 96, 111101
(2006); J. Baker et al., Phys. Rev. Lett. 96, 111102 (2006).

[7] B. Abbott et al. Phys. Rev. Lett. 116, 061102 (2016).

[8] P. Havas, "The early history of the problem of motion in General Relativity," in *Einstein and the History of General Relativity*, edited by Don Howard and John S. Stachel. Einstein Studies Vol. 1, 1989.

[9] D. Kennefick, "Einstein and the problem of motion: a small clue," in *The universe of General Relativity*, edited by A.J. Kox and Jean Eisenstaedt. , Einstein Studies Vol. 11, 2005.

[10] D. Lehmkuhl, "General relativity as a hybrid theory: The genesis of Einstein's work on the problem of motion," *Studies in History and Philosophy of Modern Physics*, Vol. 67, 2019.

[11] D. Salisbury, *A contextual analysis of the early work of Andrzej Trautmann and Ivor Robinson on equations of motion and gravitational radiation*, https://arxiv.org/pdf/1910.03753.pdf, which arguably, is the only work that is not restricted to the 1920s and 1930s. It pioneered research on Andrzej Trautmann's and Ivor Robinson's work on the problem of motion in the 1950s and 1960s.

[12] See, e.g., P. Ruiz de Olano et al., "Taking approximations seriously: The cases of the Chew and Nambu-Jona-Lasinio models," *Studies in the History and Philosophy of Science*, Vol. 93, 2022.

[13] A. Borrelli, "Monte Carlo Event Generators as Tools of Theory in Early High Energy Physics," *NTM Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin*, Vol. 27, (2019).