RELATIVISTIC ASTROPHYSICS OF THE TRANSIENT UNIVERSE

In this decade, the Transient Universe will be mapped out in great detail by the emerging wide-field multiwavelength surveys, and neutrino and gravitational-wave detectors, promising to probe the astronomical and physical origin of the most extreme relativistic sources. This volume introduces the physical processes relevant to the source modeling of the Transient Universe.

Ideal for graduate students and researchers in astrophysics, this book gives a unified treatment of relativistic flows associated with compact objects, their dissipation and emission in electromagnetic, hadronic and gravitational radiation. After introducing the source classes, the authors set out various mechanisms for creating magnetohydrodynamic outflows in winds, jets and blast waves and their radiation properties. They then go on to discuss properties of accretion flows around rotating black holes and their gravitational wave emission from wave instabilities with implications for the emerging gravitational wave experiments. Graduate students and researchers can gain an understanding of data analysis for gravitational-wave data.

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RELATIVISTIC ASTROPHYSICS OF THE TRANSIENT UNIVERSE

Gravitation, Hydrodynamics and Radiation

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To our parents

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Foreword

Some of us only rarely stop to stare at the night sky, with the naked eye, let alone with binoculars or a telescope. And when we do, the heavens may seem to be majestic, peaceful, and eternal. This impression, however, is deceptive. The Universe is a magnificently violent place. Gigantic clouds contract and ignite, producing the large and fiercely burning globes that we call stars; these stars, in turn, can explode in flashes that are more luminous than millions of suns, and they can do this in a multitude of ways. Pairs of stars may coalesce, again giving rise to unimaginable outbursts of energy. Black holes may form, whose gravitational attracting force is so huge that neighboring stars, planets and gases may be accelerated to reach velocities nearing that of light, being torn apart in the process, unless they are black holes themselves.

At larger distance scales, events take place at much slower rates: galaxies devour smaller galaxies, black holes millions or even billions of times heavier than our Sun devour other objects in the central regions of galaxies. And the most catastrophic happening of all is the creation process of the Universe itself, the big bang.

Conversely, in other cosmic events, and at the smallest distance scales, atomic nuclei and subatomic particles are blown away and reach kinetic energies so enormous that no man-made laboratory, such as the Large Hadron Collider at CERN, will ever be able to match them.

Compared to all this violence, our planet Earth is amazingly peaceful and quiet. The vast emptiness of our Universe keeps us at a safe distance from all those brutal happenings; a convenient atmosphere shields us from the extremely energetic subatomic particles roaming around in space. It also moderates and filters the solar radiation. We are safe.

In fact, we can choose locations that are quiet enough to house the most sensitive scientific equipment possible to detect the minute effects of gravitational waves. These waves must originate from several of those violent outbursts described above, but because gravity is essentially an extremely weak force, gravitational waves are notoriously difficult to detect. All our technical skills and ingenuity have not yet been successful in this respect, but this may change in the near future.

Maurice H. P. M. van Putten and Amir Levinson have done a miraculous job in listing all those cosmic catastrophes taking place around us, fortunately safe distances, and they describe every possible detail of how these events can be studied and understood in a cosmic context. All of this is physics, and even though we cannot mimic any of these phenomena at full scale, we have indeed learned how to understand them just by extrapolating all those laws of nature that we have learned to describe and exploit.

Anticipating the possible detection of gravitational waves, we do the best we can to predict the expected wave forms; the more accurate templates that we can produce have the highest potential of being detected first, while establishing the *absence* of the predicted wave forms, by a statistical analysis, may equally well serve to give us further information about the Universe we live in.

The tax agency in our country once advertised with the slogan: *We can't make this more enjoyable, but we can make filling out your tax forms a lot easier for you*. Shortly after that, a mathematician entitled his inaugural lecture as follows: *I can't make it any easier for you, but certainly I can make it a lot more enjoyable*.

Van Putten and Levinson did not write an easy text, but they did make an enjoyable compilation of all those strange things that can happen in our Universe, not only providing detailed physical calculations to understand them, but also including descriptions of all the channels of radiation that we can use to receive as much information about them as we can.

Gerard 't Hooft
Institute for Theoretical Physics, Utrecht University

Preface

In this decade, we anticipate a complete window for observing the Universe with advanced multimessenger survey instruments for electromagnetic radiation, cosmic rays, neutrinos and gravitational waves.

The evolution of the Universe is largely shaped by gravity, giving rise to large scale structure in filaments and voids down to galaxies and their constituents. The associated radiative phenomena indicate an "arrow of entropy" that points to scales generally less than 1 Mpc, where we find interactive and transformative processes such as galaxy mergers, active galaxies, supernovae and gamma-ray bursts (GRBs). On these scales, the Transient Universe serves as a cosmic beacon in the era of reionization to the present. Thus, entropy appears to be increasing, from an initially low value at the birth of the Universe as conjectured by Penrose, with conceivably jumps in some of the brightest and most extreme transient events.

Multimessenger astronomy aims at the measurement of physical and astronomical parameters across various observational windows, in and beyond the electromagnetic spectrum. It promises a probe of gravity with the potential to discover the relationship between large structure formation by dark matter, galaxy formation, star formation and their end products, to unravel the astronomical origin and physical mechanism giving rise to active galactic nuclei, core-collapse supernovae (CC-SNe) and GRBs.

Ultra-high energy cosmic rays (UHECRs) and cosmological GRBs stand out as the most relativistic transient events that may be telling us about gravitation in the strongly nonlinear regime in the spacetime around black holes. Since black holes are scale free, we expect common principles at work by which supermassive and, respectively, stellar mass black holes induce high energy non-thermal emissions. High energy emissions around black holes provide signatures not only of the geometry of spacetime, but of how geometry induces novel radiation processes. The latter is widely believed to involve rotating black holes and possibly merging black hole binaries. Since gravitation is universal, we further anticipate that radiation processes induced by gravitation extend across a broad range of emission channels.

Some of the emerging multimessenger detectors offer wide-area surveys of the time-dependent Universe. They will give us a census of transient sources, their astronomical origin and host environments and, at high redshifts, their earliest cosmological manifestations. For instance, the first GRBs will track the formation of the first stars, and hence point to the first galaxies that might harbor the seeds of supermassive black holes.

The Transient Universe is observable in electromagnetic, hadronic and gravitational radiation processes. In existing curricula, these three processes are typically dispersed over a wide variety of courses in theoretical astrophysics and astronomy. Yet, observations on the Transient Universe stimulate a broader development towards a unifying picture. This book intends to provide a practical introduction along with examples of source modeling and some related data analysis techniques. These examples are directed to stimulate further innovation on multimessenger data analysis of, e.g., CC-SNe, GRBs and their associated gravitational-wave emissions.

It is advised that contemporary reviews are consulted to accompany some of our discussions. We do not claim to be complete but, rather, to provide a hands-on introduction serving those who wish to enter this exciting new field in a format suitable for a one-semester graduate course.

Much of this book developed out of research, lectures and seminars developed by the authors at the Korea Institute for Advanced Study, Tel Aviv University, DAMTP at the University of Cambridge, Osservatorio di Capodimonte (INAF-Napoli), LIGO-Caltech, Le STUDIUM IAS and LPC2E at CNRS-Orléans, the Universities of Orléans, Tours and Nanjing. In our teaching, we commonly recommend supplementary reference books on general relativity by Hawking and Ellis [275], Chandrasekhar [141], Wald [632] and ’t Hooft [576], on electromagnetic radiation processes in astrophysics by Ribicki and Lightman [520] and Dermer and Menon [178], on neutrino physics in astrophysics by Giunti and Kim [244], on fluid dynamics by Chandrasekhar [140] and Batchelor [72], on compact objects by Shapiro and Teukolsky [533], and on active galaxies by Krolik [352].

We begin with an overview of transient sources and essential elements of relativistic radiation processes, hydrodynamics and magnetohydrodynamics associated with compact objects, curved spacetime and gravitational waves, blast waves, outflows and jets, some principles of thermodynamics of stellar systems and accretion disks. We apply some of these ideas to an outlook on non-thermal radiation processes around Kerr black holes.

The material presented in this book grew out of discussions with many colleagues. We wish to thank in particular Ski Antonucci, Barry Barish, Jacob Bekenstein, Roger D. Blandford, Stefano Bolognesi, Adam Burrows, E.E. Cheng Young, Edna Cheung, Massimo Della Valle, Charles D. Dermer, David Eichler, Andrew C. Fabian, Gabriele Veneziano, Alok Gupta, Chung Wook Kim, Serguei Komissarov, Kimyeong Lee, Nobuyuki Kanda, Roy Kerr, Shrinivastas Kulkarni, Fujimoto Masa-Katsu, Yuri Lyubarsky, Ehud Nakar, Changbom Park, Tom Prince, Graziano Rossi, Alessandro D.A.M. Spallicci, Erik Verlinde, Michel Tagger, Hideyuki Tagoshi, Daisuke Tatsumi, Gerard't Hooft, Kip S. Thorne, Henk van Beijeren, Eli Waxman, Piljin Yi and Fabian Ziltener for stimulating discussions, and Claire L. Poole of Cambridge University Press for her continuous attention to detail in finalizing the manuscript.

Notation

The conventional metric signature is $(-, +, +, +)$. The Minkowski metric is given by $\lceil -1, 1, 1, 1 \rfloor$.

Tensors are written in the so-called abstract index notation. Indices from the middle of the alphabet denote spatial coordinates. Four-vectors and p-forms are also indicated in small boldface. Three-vectors are indicated in capital boldface.

The epsilon tensor $\epsilon_{abcd} = \Delta_{abcd}\sqrt{-g}$ is defined in terms of the totally antisymmetric symbol Δ_{abcd} and the determinant g of the metric, where $\Delta_{0123} = 1$, which changes sign under odd permutations.

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Even if there is only one possible unified theory, it is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe?

Stephen W. Hawking (1942–)

Hawking, S.W., 1988, *A Brief History of Time* (New York: Bantam Dell).

It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is – if it disagrees with experiment it is wrong. That is all there is to it.

Richard P. Feynman (1918–1988)

From a lecture given by Feynman. With permission from Caltech and the Feynman estate.

And these little things may not seem like much but after a while they take you off on a direction where you may be a long way off from what other people have been thinking about.

Roger Penrose (1931–)

From a program transcript "Sir Roger Penrose" interviewed by Adam Spencer and aired on Australia's ABC 'Quantum' program on Thursday 6th April 2000.

In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side; an effort which has not yet been made, or at least, only to a limited extent.

Victor Francis Hess (1883–1964)

Les Prix Nobel, 1936 © The Nobel Foundation. In 1998, *Nobel Lectures in Physics 1922–1941* (Singapore: World Scientific Publishing Co.).

To this day I always insist on working out a problem from the beginning without reading up on it first, a habit that sometimes gets me into trouble but just as often helps me see things my predecessors have missed.

Robert B. Laughlin (1950–)
Les Prix Nobel, 1998 © The Nobel Foundation.
In Ekspong, G., 2002, *Nobel Lectures in Physics 1996–2000*
(Singapore: World Scientific Publishing Co.).

There are two possible outcomes: if the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery.

Enrico Fermi (1901–1954)
Fermi, E. As quoted in Jevremovic, T., 2005,
Nuclear Principles of Engineering (New York: Springer).

Status quo, you know, is Latin for "the mess we're in."

Ronald W. Reagan (1911–2004)
With permission from the Ronald Reagan Presidential Foundation and Library.

Behind it all is surely an idea so simple, so beautiful, that when we grasp it–in a decade, a century, or a millennium–we will all say to each other, how could it have been otherwise? How could we have been so stupid?

John Archibald Wheeler (1911–2008)
Wheeler, J. A., How come the Quantum.
Annals of the New York Academy of Sciences, **480** (1986), 304–316.

Two paradoxes are better than one; they may even suggest a solution.

Edward Teller (1908–2003)
Teller, E., Teller, W., & Talley, W., 1991,
Conversations on the Dark Secrets of Physics (New York: Basic Books)

A fact is a simple statement that everyone believes. It is innocent, unless found guilty. A hypothesis is a novel suggestion that no one wants to believe. It is guilty, until found effective.

Edward Teller (1908–2003)
Teller, E., Teller, W., & Talley, W., 1991,
Conversations on the Dark Secrets of Physics (New York: Basic Books)