ADVANCES IN COSMOLOGY

science

philosophy

art

Editors

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ENRICO MAGNANI

Springer

Advances in Cosmology

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Cristiano Galbiati · Enrico Magnani
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Philosophy is written in that great book which ever lies before our eyes—I mean the universe—but we cannot understand it if we do not first learn the language and grasp the symbols, in which it is written. This book is written in the mathematical language.

Galileo, Il Saggiatore (1623)

Foreword

Where do we come from? How did everything begin? How did everything evolve? These questions have interested humankind for thousands of years. People have always been intrigued by the sky and the celestial phenomena they observed, leading them to the science of astronomy, expanding their horizon way beyond the Earth's atmosphere. Later, with the emergence of new technologies and methods, including spectroscopy, a new field emerged: astrophysics. Whereas astronomy deals with celestial objects, space and the physical universe as a whole, astrophysics focusses on the physical processes associated with the objects that form the universe. Both are intimately connected.

According to NASA, the definition of cosmology is "the scientific study of the large scale properties of the Universe as a whole". But you cannot fully understand the large-scale properties without understanding the small scales. Observations of phenomena such as the cosmic microwave background, together with the results of the Standard Model of particle physics, place constraints on the physical conditions that must have prevailed in the early universe. In parallel, phenomena discovered through cosmological observations, such as dark matter and non-zero neutrino mass, suggest the presence of new physics: physics beyond the Standard Model. Answering fundamental questions on our universe, its origin and development, brings researchers and scientists from different fields together. By working together, not only in their respective domains but also across the disciplines, scientists can take great steps in understanding. Collaboration is the key to progress and this book emphasizes this kind of scientific interconnection.

Spreading the net further we should not forget the important role of philosophy. The ancient philosophers were the first to develop an understanding of nature through power of mind alone, described through mathematical principles. We clearly see the interconnectedness of astronomy, astrophysics, astroparticle and particle physics, and philosophy. From the last chapter of Werner Heisenberg's book "Philosophy and Physics", one can conclude that in the course of history it repeatedly turns out that fundamental questions of philosophy related to nature are in reality questions of physics. Philosophy and physics inspire each other, learn from each other.

Art, too, has an important place in humankind's contemplation of the universe. There should be no two cultures: intellectual life should be united in a single culture. Why ? Because reality is very different from what we are able to grasp with our miniscule awareness. We need tools that can take us further. There is as little room in our ability to grasp reality for an infinite Universe with boundaries as there is for a Big Bang. Art, however, sets out to expand our awareness, to create room for new concepts that are just now being researched in science. Or, as Paul Klee once said, art does not reproduce the visible; rather it makes things visible. The same applies to science, especially pure research: it goes far beyond the visible. Sometimes, it is the visions of science that open up new forms to art, and sometimes it is the other way around. Art and science pursue similar visions and I like the idea of Enrico Magnani using the shore as a of merging art with science. Both art and science deviate from the beaten track of thought and perception to conquer something new with great purpose and creativity. Both risk going down the wrong path when wanting to discover new territory. Neither has it easy, because they question the tried and tested and upend the familiar. The mindsets of artists and scientists are very similar. Often they made a choice early in their careers between science and art. Julius von Bismarck, the first artist in residence at CERN, and Enrico Magnani are just two examples. It is art, science and philosophy together that best advance humankind.

Advancement is a complex beast, but it relies on the wellspring of curiosity. We make progress in understanding our world, are exploring others, have put ourselves in a position not only to contemplate the nature of our universe, found exoplanets and made the lives of ordinary people unimaginably better than before. It is fundamental research that forms the basis for all kinds of scientific research. If you had asked Wilhelm Roentgen to invent a tool or a method to show illness or imperfections in the body, he would never have thought of X-rays. Innovation is a virtuous circle linking basic to applied science. Synergy between research and innovation results not only in societal and economic impact but also, and very importantly, in the creation of enhanced opportunities for further developments. This circle, its connection to, and synergies with, other domains of human enquiry needs to remain strong, to be unbroken.

I am sure this book will give you a first glimpse how much the different research areas are interconnected and how much each learns from the others and their respective technologies. It is so important to reach beyond the boundaries of our own research. Doing so brings us forward and helps us to better understand each other, and to better appreciate the universe we share.

Enjoy reading.

February 2022

Rolf-Dieter Heuer
President Council of SESAME,
Director General CERN (2009-2015)
Al Balqa, Jordan

Preface

An unprecedented variety of approaches is available today to researchers whose job is to explore and understand the origin, the structure, the destiny and the laws governing the Universe. This is the underlying reason for this book, whose main motivation is to present Cosmology in its multi-disciplinary aspects as a scientific, philosophical and artistic quest. Since the dawn of time, humans have looked at the sky in an attempt to understand their origins, and the laws governing and influencing them. In most ancient civilizations, astronomers embodied the very power of knowledge. Knowledge was not compartmentalized and their scientific quest often had philosophical implications and visual representations. Natural sciences in those times had no borders. The journey from Astronomy to today's Cosmology has been a long one. Scientists today formulate theories that have to be proven experimentally using the available tools, and this is a very complex process involving the establishment of international collaborations and global networks.

Contemporary cosmology is looking at the Universe as a whole and in the chapters of this book, researchers from all fields explain the ideas, instruments and technologies that are driving the search, what we know and what will be done, through the effort and competence of thousands of experts, to explore and decipher what is still obscure and unknown. Cosmology has been and is the realm of astronomers, physicists and philosophers and, in the past, it inspired religious and mythological cosmogonies.

In 1584, Giordano Bruno, a Dominican friar and philosopher, published the philosophical-cosmological dialogues between Albertino, Burchio, Elpino, Filoteo and Fracastorio in "De l'infinito Universo et Mondi". After demonstrating the infinity of the universe from a logic and theological point of view, Filoteo says "Questo è quel che io dovevo aggiongere. Perché, dopo aver detto l'universo dover essere infinito per la capacità ed attitudine del spacio infinito, e per la possibilità e convenienza dell'essere di innumerabili mondi, come questo; resta ora provarlo... (This is indeed what I have to add; for, having pronounced that the universe must itself be infinite because for the capacity and aptness of infinite space; on account also of the possibility and convenience of accepting the existence of innumerable worlds like our own; this now still remains to be proven…" (https://www.faculty.umb.edu)).

Scientists are guided in their investigation of Nature by ideas brought by philosophers said in 2013 quantum physicist Francesca Vidotto. The curiosity to understand where we come from and where we are going to is without doubt a strong driving force. What happened during and after the Big Bang, will the accelerated expansion of the Universe continue or the ultimate fate of the Universe is to end in a Big Rip instead of a Big Crunch? These are some of the many questions with philosophical implications raised by modern cosmology.

Many topical researches are at the interface between particle physics, astrophysics and cosmology, offering challenges and opportunities to each of these fields in a common endeavour. Cosmology has been exploring the early and the late universe. Particle physicists have been studying the fundamental elementary particles, the smallest constituents of matter, and their interactions, the properties of antimatter as well as trying to unveil the reasons for the observed matter-antimatter imbalance. Astrophysicists have been studying the nature of astronomical objects and phenomena. However, many still unresolved questions in cosmology are today of common interest. In fact, understanding the origin and nature of dark matter, elucidating the baryon asymmetry, might provide insight into our understanding of the early universe. Will a breaking of the standard Lambda–cold-dark-matter model of cosmology help to elucidate dark matter, dark energy and gravity? Will answer to such questions come from accelerators, telescopes or gravitational waves? Or will the answer come from combined efforts of interacting disciplines? Many are the physicists working to validate or to rule out with experimental data some of the theoretical models proposed, trying to find the model that unifies all forces of nature, describing with a single theory all the phenomena in the Universe, from large to subatomic scale. Thanks to the new technologies, instruments and new probes, as well as their current analysis capability, scientists will provide answers to cosmological questions related to the early universe, thus unveiling new physics. The next decade will surely see theoretical and experimental physicists and astrophysicists analysing and combining the multi-messenger observations collected, thus contributing to a big step forward in our understanding of the early and late Universe, a Universe that they say is 13.7 billion years old. Asking ourselves "Does the Universe have a beginning?" "Do physical laws and causality apply to the universe as a whole?" is asking scientific questions with a philosophical meaning. The discourse about the laws of nature underlying the Universe is expressed in mathematical terms, as Galileo said, and science will continuously push the boundary of human knowledge in the attempt of providing a rational explanation of the world, whereas artists and philosophers will contribute by facilitating our understanding and by stimulating our perception. Clearly, any scientific truth is precarious, as it stays valid until it is not disproved, and this makes scientific knowledge an endless process.

The first section of the book "From Astronomy to Modern Cosmology" is written by renowned theoretical physicists and is divided into three parts, reviewing the past knowledge and assumptions as well as the new theories and ideas, most of them driving experimental research. Modern cosmology started with the paper "Cosmological Considerations of the General Theory of Relativity" by Einstein, who is considered the Father of Modern Cosmology, and the many observations and discoveries of the twentieth century. Ugo Moschella gives a comprehensive historical overview from Galileo to Einstein. Gabriele Veneziano, who is considered the Father of the String Theory, explains the importance of quantum mechanics for modern cosmology and Kai Schmitz gives an overview of the most modern theories that are driving the contemporary experimental research. Schmitz's research has been recently focussing on the connection between gravitational waves and cosmic strings, with an aim to understand the symmetries and forces that governed the universe during the first moments of its existence.

The second very extensive section, entitled "Dark matter, dark energy, black holes, star formation and other cosmological searches", is presenting how today's experimental research in Cosmology is not the kingdom of a specific area of competence and how the quest for fundamental laws can be and is tackled from different angles, using very different and highly sophisticated technologies, from particle detectors in high-energy accelerators or with detectors placed in space or underground caverns, to telescopes and gravitational wave interferometers. The combined efforts of such large communities of scientists provide remarkable added value in terms of ideas, approaches and competences and are giving a positive push to the cosmological quest.

HEP Physicists at CERN have the tools (particle energy, data analysis capability, etc.) and theories allowing them to search directly or indirectly for Dark Matter at the LHC experiments: ATLAS, CMS and LHCb and, more recently, FASER. Other fixed target experiments (NA64) and others at the Antimatter facility (BASE) are also searching for dark photons, axions or axion-like particles. The search for solar axions started at CERN with CAST, an experiment that started to take data in May 2003 and also, more recently, other experiments aimed at detecting chameleon particles that should be produced when dark energy interacts with the photons; all particles that have not been found yet. The LHC upcoming Run 3 and the High luminosity upgrade are expected to contribute significantly to providing answers to the main unsolved questions of dark matter and dark energy, hopefully showing signatures of some of these elusive particles. After an introduction by Sushita Kulkarni, a theoretical physicist from Graz University leading research on Dark Matter and neutrinos phenomenology with the aim to bridge theories with experimental searches, Caterina Doglioni and Dan Tovey, Deborah Pinna, Carlos Vázquez Sierra and José Francisco Zurita, Marios Maroudas and Kaan Oyboyduman, Michaela Queitsch-Maitland, Dipanwita Banerjee, Stefan Ulmer take us to exploring the tools used in their collaborations to unveil the elusive cosmological signatures that will hopefully let us make the step forward beyond our current understanding.

From CERN, the journey continues on board of the ISS (International Space Station) with the chapter "The AMS experiment on the International Space Station", by Maura Graziani and Nicola Tomassetti. They tell us how the observation of 194 billion cosmic ray events recorded from the start of the operation of the detector (May 2011) to November 23, 2020 in a collaboration of 44 institutions from the

USA, Europe and Asia has provided key information on the origin of cosmic ray electrons, the propagation of cosmic particles and how they are using this knowledge to understand cosmic dark matter and antimatter. Claudio Bortolin and Paola Catapano, in their "The right key- Four spacewalks to repair the Alpha Magnetic Spectrometer on the International Space Station", tell us about the challenges of the spacewalks conducted by Italian Astronaut Luca Parmitano (ESA) with his US colleague Drew Morgan (NASA) for the crucial repair which enabled the full functionality of AMS-2. The detector is expected to take data until the ISS remains in orbit.

"Under the Gran Sasso" by Cristiano Galbiati and Walter Bonivento takes us to the underground area beneath the Gran Sasso mountain and the Laga National Park in Italy, where astrophysics research for WIMPs (Weakly Interacting Massive Particles), a Dark Matter candidate, using the Argon (DarkSide-20k) or Xenon (XENONnT) detectors is conducted. They tell us about their choice to use Argon and the technologies developed to reach the needed zero background. The collaboration says it is not axions or physics beyond standard model.

"Gravitational waves: Why and How" by Federico Ferrini, former Director of EGO (European Gravitational Observatory) at the time when the first gravitational wave signals were observed, introduces non-specialist to the fascination of the gravitational universe and explains how gravitational wave cosmology started and developed. Interesting to note that since the first detection in September 2015 to November 2021, the LIGO, Virgo and KAGRA interferometers recorded 90 events or cosmic quakes (79 of them have been recorded between April 2019 and March 2020), generated by the merging of black holes, neutron stars or even of a neutron star with a black hole. The analysis of the information provided by these events is expected to give new clues on how stars live and die. Interferometers are today key cosmological probes to understand the gravitational Universe.

Looking at the sky with a telescope has been the way in which astrophysicists have explored stars, planets, galaxies and our solar system since the dawn of science. The chapter by Gianni Marconi and Riccardo Scarpa entitled "Big telescopes and observatories: hi-tech challenges for great astronomical science" gives an insight into optical astronomy and the work of astrophysicists today. As Massimo Tarenghi, Astrophysicist and former Director of VLT and ALMA, once said *In the old times, I was looking through an eyepiece for hours, had to make sure that the telescope was not going away from a guiding star and the record was done using a photographic plate. What a change to today's modern instruments!* To make precise astronomical instruments requires considerable human toll, the effort of large communities of researchers and a crucial follow-up with industrial partners. Many high technological developments are involved in the production of mirrors and the infrastructures allowing very precise movement of these gigantic structures. Just as an example, the European Extremely Large Telescope (E-ELT) has a 39-m-diameter mirror. Several scientific communities are using the telescope at different times looking at the origin of signals farther out in space and further back in time. The bigger revolution in the astronomical science, at the same time as that of the instruments, regards the way in which data is collected and processed, thanks to the creation of big archives accessible to astrophysicists that analyse the data and use them in a variety of ways and for a variety of purposes. Telescopes scan the sky recording tiny changes; new sophisticated telescope platforms measure the strength of gravitational waves produced during the epoch of inflation 380.000 years after the Big Bang. Cosmic-microwave background (CMB) measurements in multiple frequency bands allow the removal of the galactic foreground. The JWST telescope launched on 25 December 2021 is showing sharp images and has already discovered a candidate new galaxy, the Maisie's galaxy, so far the most ancient ever observed 300 Myr after the Big Bang.

JWST is opening new revolutionary avenues to understanding the origin of our Universe and the early evolution of galaxies as well trying to elucidate the existence of dark matter.

In chapter "Other worlds in the cosmos: from philosophy to scientific reality", Michel Mayor, Nobel prize laureate for physics in 2019, with Jim Peebles and Didier Queloz, for the discovery of exoplanet *51 Pegasi b* orbiting a solar star, with other young professors from the University of Geneva, Emeline Bolmont, Vincent Bourrier, David Ehnreich and Bern, Christoph Mordasini are bringing us to discover the habitability, the upper atmosphere and the atmosphere of the exoplanets and their formation. The existence of exoplanets originated from a philosophical assumption before it was scientifically proven. Today, the analysis of planetary atmospheres may reveal spectral characteristics induced by the development of life; advances in spectroscopy studies of exoplanets, as the authors say, make the search for extraterrestrial life possible. According to NASA, 4000 exoplanets have been discovered and confirmed so far and about 1000 more candidates are on the waiting list.

The third section, on Philosophy, focusses on the link existing between science and philosophy. In the past and until the eighteenth century, there was no dividing line between the scientific disciplines and philosophical considerations were often associated with scientific observations; some representations to explain the advancements in natural sciences as well as by astronomers can be seen as pieces of art. It is worth to remember that at CERN and elsewhere the Bell theorem with the locality and causality assumptions and the Bell's inequalities have been debated not only for their scientific but also for their philosophical implications. Today, Cosmological philosophy starts to be a domain by itself. Francesca Vidotto, a theoretical physicist whose research is focussed on Loop Quantum Gravity and, in particular, on spinfoam Cosmology, explains in the chapter "Space, time and matter in the primordial Universe" that formulating a new theory of understanding brings scientists to the edge of knowledge where philosophy and experience must meet.

The fourth and final section is dedicated to Art. Enrico Magnani, a nuclear engineer by training and currently a full time artist, presents his artwork, which recently focussed on Supernovae, Dark Matter and Multiverses, in a chapter entitled "The shore between Art and Science". The chapter tries to answer questions such as how much technology is affecting the artistic work, how much scientific ideas are nurturing art and how much scientists have been inspired or contributed to art and philosophy. It also identifies some common traits in artistic and scientific research: the quest to unveil the mystery, to push the boundaries of human knowledge more and more into the unknown, using beauty and intuition as a compass. Science, Philosophy and Art are expressions of a common quest: the necessity we pursue since the dawn of time, to understand the world and the universe we are living in and of which we are an integral part.

The divide between cultures has been a long and debated issue since Charles Snow invoked the gap between science and humanities. The present book not only explains where we stand today in Cosmology and what are the main questions and the tools and ideas to provide scientific answers, but it also establishes a dialogue between cultures, based on knowledge, in an attempt at crossing the existing boundaries and making the gap less deep.

We do wish you happy reading.

Wien, Austria
Geneva, Switzerland
February 2022

Marilena Streit-Bianchi
Paola Catapano

Acknowledgements

The editors would like to warmly thank all the authors who have embraced this project and contributed with their valuable texts and illustrations to make this book interesting and attractive. We also thank *Springer Nature* and, in particular, *Springer's* Executive Editor Marina Forlizzi for her valuable support and assistance in the making of this book. The amount of ideas and research going on in the many sectors of physics and astronomy and the technological developments that made the most recent research in Cosmology possible are presented. The book outlines how today multi-disciplinary approaches are fruitfully contributing to the search that is trying to bring out the dark from the unknown. The knowledge and assumptions cosmologists are making today, both at theoretical and experimental levels, in tackling the origin and development of the universe, and how this human questioning is also pervading philosophy and art will accompany the reader through a long journey of discovery.

In most ancient civilizations, astronomers incarnated the power of knowledge. We intended, by connecting Science with Philosophy and Art, to remind people that many of the questions science asks at fundamental levels are a quest of our humanity. To conclude, using the words of one of the authors: R*esearch, Beauty, Intuition, Curiosity are the elements that we find on the shore between art and science.*

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About the Editors

Marilena Streit-Bianchi was born in Rome (Italy). She received a Doctorate in Biological Sciences from the University of Rome and joined CERN, the European Organization for Nuclear Research in Geneva (Switzerland), in 1969. She has been a pioneer in the study of high-energy particles produced by accelerators for cancer treatment. She has held managerial positions on safety training and technology transfer, has been a senior honorary staff member at CERN and is actively engaged in art and science as a book editor and curator of exhibitions in Europe and Mozambique. She is the Vice President of the International Association ARSCIENCIA and member of the Italian Physical Society (SIF). She has been one of the editors of the book "Mare Plasticum-The Plastic Sea. Combatting Plastic Pollution Through Science and Art".

Paola Catapano was born in Lucera (Italy). She is a Science Journalist and Science Communicator at CERN. In 1987, she graduated in simultaneous interpreting from the University of Trieste and in 1997 she obtained a master's degree in Science Journalism from ISAS (International School for Advanced Studies), Trieste. At CERN since 1990, she has covered several positions from assistant to the Director General Carlo Rubbia, to leader of public outreach. She is currently head of the editorial content production in CERN's Education, Communication and Outreach group. In 2010–11, she authored and hosted the TV program DIXIT Scienza for the Italian National Television, RAI. She created and led the research expedition to the Arctic Polarquest 2018, whose program included historical exploration, measurements of cosmic rays, drone mapping of uncharted territories and plastic debris sampling until the 82°nd parallel (cf. and book "Mare Plasticum-The Plastic Sea-Combatting Plastic Pollution Through Science and Art"). She has participated in several Science Festivals and won international awards and is the author of the book *Il lungo viaggio delle onde gravitazionali*, Textus, 2021.

Cristiano Galbiati was born in Milano (Italy). He is a Particle Physicist with a Ph.D. from the University of Milan. He is Full Professor at the Physics Department of Princeton University (Princeton, New Jersey) and Professor of Particle Astrophysics at the Gran Sasso Science Institute (L'Aquila, Italy). His research has been on solar neutrinos and is at present Coordinator of the international experiment DarkSide at the INFN Gran Sasso National Laboratory and of the project Aria at Monte Sinni in Carbosulcis (Gonnesa, Sardinia), searching for dark matter. Besides his many scientific publications, he is the author of the book *Le entità oscure. Viaggio ai limiti dell'Universo,* Feltrinelli, 2020.

Enrico Magnani was born in the province of Reggio Emilia (Italy). He is an internationally recognized artist whose work integrates art, science and transcendence. He graduated as nuclear engineer at the Polytechnic University of Milan in 2004 and worked as a Researcher at the Karlsruhe Institute of Technology (KIT) for the nuclear fusion projects ITER and DEMO (2006–2010). He has been painting and doing artworks since his young age and at a certain point in his scientific career, feeling that knowledge only based on rational speculations was not fulfilling his life, he decided to dedicate himself entirely to art. After the first figurative period (1995–2006), his work became more and more abstract, using various kinds of materials and techniques. His work has been presented in museums, foundations, private galleries and public institutions in Europe and the United States. In 2017, he started a series called "Supernova" and in July 2019 he exhibited at CERN his "Searching the Unknown—The Dark Matter Collection". In autumn 2020, he completed his permanent installation "Quintessence", now visible at the INFN Gran Sasso National Laboratory in L'Aquila. He holds seminars and training workshops on creativity.

From Astronomy to Modern Cosmology

Looking at the Sky: From Pythagoras to Einstein Through Galileo and Newton

No Admission Without Knowledge of Geometry

Ugo Moschella

The material world—the reality—is not something given, but is born with us. For the "given" to become reality, it must be resurrected in the literal sense of the word. This is the role of Science, this is the role of Art.

[a]Ossip Mandelstam, Letter to Marietta Shaginyan, April 5, 1933.

1 Prelude

E quando miro in cielo arder le stelle;
Dico fra me pensando:
A che tante facelle?
Che fa l'aria infinita, e quel profondo
Infinito Seren? che vuol dir questa
Solitudine immensa? ed io che sono?
…
E dell'innumerabile famiglia;
Poi di tanto adoprar, di tanti moti
D'ogni celeste, ogni terrena cosa,
Girando senza posa,
Per tornar sempre là donde son mosse;

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Uso alcuno, alcun frutto
Indovinar non so.[1]

Giacomo Leopardi's wandering shepherd looks up into the sky, searching for the meaning of all things (*A che tante facelle?*) and of its very life (*ed io che sono?*). The attempt to find in the skies the point and the purpose of all the nowhere-going movements and struggles of everything and every human being (*di tanto adoprar, di tanti moti*) is doomed to failure (*Uso alcuno, alcun frutto / Indovinar non so*).

The questions raised by the shepherd have been asked by men and women of all epochs, though rarely expressed with such intense words. The gesture of looking at the starry sky seems to be specific to the genus homo as much as the *nosce te ipsum* [1] to such an extent that it could be also taken as a definition of what being human is all about.

The terrestrial landscape has changed a great deal, but, to the naked eye, the sky has not changed at all, because the couple of million years elapsed after the appearance of the first *homines* on Earth are, on a cosmic scale, *like a day that has just gone by, or like a watch in the night*.[2]

All men and all women have seen the same sky. Yet, their cosmogonic narrations and their cosmological representations are very different from each other and above all are radically different from that which is supposed to be the modern scientific vision of the world, our vision. The story of the ideas that led to this vision is extraordinarily fascinating, dramatic and sometimes tragic and has been narrated a thousand times in books that have rightly become classical. We will go over some of its highlights again [2].

2 A Name, an Idea

The idea of universe is not a primitive idea [3]. If, as customary, we let history begin with the invention of writing around the year 3000 BC, we see that humanity was able to do without the idea of universe, or, better to say, its explicit thematization, during half of its history, not to mention the immensity of prehistory: a word to designate the totality in a unified way appeared in Greece only around the year 500 BC.

Previously, a more or less exhaustive enumeration of the things contained in the totality or else a binary opposition were used—the biblical and Homeric formula *Heaven and Earth* being the best known. It is only when this distinction between the things on which we can—in principle—have an influence and those which are

[1] *…And when I gaze upon the stars at night – In thought I ask myself – "Why all these torches bright? – What mean these depths of air, – This vast, this silent sky, – This nightly solitude? And what am I?" – …– "And all this mighty motion, and this stir – Of things above, and things below, – No rest that ever know, – But as they still revolve, must still return – Unto the place from which they came, – Of this, alas, I find nor end nor aim!"*
Giacomo Leopardi, Canto notturno di un pastore errante dell'Asia (excerpt) 1830.

[2] Psalms 90, 4.

completely beyond us is put aside, that the "world" can appear. Wittgenstein expresses this state of affairs with the formula "The subject does not belong to the world, but it is a frontier of the world".

Legend has it, that was Pythagoras to choose the proper noun: "cosmos", which, as everyone knows, opposes itself to chaos and designates order and beauty, or to say it better, the beauty that derives from the order. "Pythagoras was the first, who named the encompass of the whole a Cosmos, because of the order which is in it" [4].

The Latin name "mundus" has exactly the same meaning as cosmos.[3] Pliny the Elder tells us in his *Naturalis Historia* that "The Greeks gave to all things the name 'cosmos' and we called it 'mundus' by virtue of its perfect and absolute elegance." The name "universe" (*Unvorsum*), a poetic contraction of *unus* and *versus*, appears for the first time in the fourth book of Lucretius' *De Rerum Natura*. Lucretius gives this word the meaning of a set of particles that rotate all together.

The thirtieth fragment of Heraclitus gives us a glimpse of the eternal cosmic order, that of a self-sufficient totality which does not require external instances: "This world, which is the same for all, no one of gods or men has made; but it was ever, is now, and ever shall be an ever-living fire, with measures of it kindling, and measures going out."

On the contrary, according to Plato, order does not pre-exist the primordial chaos of the chora but it results from the creative action of a demiurge. Timaeus recounts the mythical birth of the universe: "The world …has become a visible living creature containing the visible—the sensible God who is the image of the intellectual, the greatest, best, fairest, most perfect—the one only begotten heaven."

The order of the universe is not only the visible manifestation of the intelligible God; it is also the model to be imitated to return to the original state of excellence, which was lost by the incarnation of the soul. Cosmology will keep this ethical dimension for two millennia, until the birth of the scientific vision of the world. Thus, the word cosmos–order is already a "cosmology". It gives a description of the totality that is not neutral but implies a judgment of value. Perhaps, it is interesting to compare this stance with the modern point of view, exemplified here again by Wittgenstein's words: "The sense of the world must lie outside the world. In the world everything is as it is and happens as it does happen. In it here is no value—and if there were, it would be of no value." As for the means to describe and try to understand the order of the cosmos, the Greeks also explain to us the relative roles of "physics" and "mathematics": "The task of the contemplation of nature (*theoria phusikè*[4]) is to examine the substance of the sky and the stars, the power and the quality of generation and corruption, and, by Zeus!, it is capable of leading demonstrations on the subject of the size the form and the order of things. As for astronomy (*astrologia*) it does

[3] The original sense of "woman's ornament" is metaphorically turned into order and beauty, the beauty resulting from order (cosmetics). The usage was for a long time perceived as a metaphor. The "cosmic" unique usage took centuries to emerge. Mundus is the etymological source of the Italian word "monile".

[4] To perceive the *logoi* in beings is the act known as *theoria phusikè*, the second of the three stages of the spiritual life distinguished by Evagrius and the tradition that followed him [5].

not undertake to speak of anything like that, but it demonstrates the order (*taxis*) of celestial things, having declared that the sky (*ouranos*) is truly a cosmos; it speaks of forms, sizes, distances from the Earth to the Sun and the Moon, eclipses, conjunctions of stars, on the quality and quantity that are shown in their revolutions." (Posidonios, 135-51 avant J.-C.). The *theoria phusikè* has therefore the task of examining the substance of the sky and the stars. On the other hand, mathematics must be limited to saving the appearances. This warning will return dramatically seventeen centuries later.

3 Aristotle and the Ptolemaic World

Physics enters in cosmology with Aristotle: the physical foundations of the standard cosmological model of the ancient world are rooted in the Aristotelian conceptions of movement and gravity. The Stagirite distinguishes between three types of movements. Two of them occur in the sublunary world: the natural movements of falling heavy bodies (made in prevalence of earth and water) and of rising light bodies (made in prevalence of air and fire) are caused by their tendency to proceed to their "natural place"; on the contrary, violent movements require an external force as a cause.

The very existence of a natural place explains the central position and the spherical shape of the Earth. It also explains what gravity is. An apple falls because it aims to go where heavy bodies naturally go. That place is necessarily at the center of the universe, where the Earth is located (otherwise it would also end up falling there). Moreover, the Earth cannot spin around its axis nor can it revolve around the Sun because the perfect circular movement cannot exist in the changeable and corruptible sublunary world. Terrestrial creatures move on straight and irregular trajectories, because they are limited and imperfect and must seek food and help outside of themselves.

The motionless center of the cosmos is therefore not a place of delight, but rather a garbage dump where all the heaviness of the sublunary world falls. And yet it is the unique and privileged center around which the spheres of the superlunary world revolve, bringing the stars with them in their race without beginning or end.

The heavens are concentric crystalline spheres made of the fifth element: the aether or quintessence. The aether has no weight or lightness and therefore cannot go towards the center or away from it: its movement is by nature circular and uniform. Eudoxus of Cnidus, a disciple of Plato, had invented them as a calculation device but Aristotle considers the spheres of the heavens as physically existing. There are fifty-five of them and the last one is fixed and borders the finite universe; indeed, if the universe has a center, it can only be finite.

Can we bend outside this last frontier? The question makes no sense because there is no outside. There is nothing. Not even the void…"It is evident not only that there is not, but also that there could never come to be, any bodily mass whatever outside the heavens. …There is also no place or void or time outside the heaven. For in every place body can be present; and void is said to be that in which the presence of body, though not actual, is possible; and time is the number of movement. But in the absence of natural body there is no movement, and outside the heaven, as we have shown, body neither exists nor can come to exist." [6].

The world has to wait for Giordano Bruno to meet the one "who has pierced the air, penetrated the sky, toured the realm of stars, traversed the boundaries of the world, dissipated the fictitious walls of the first, eighth, ninth, tenth spheres, and whatever else might have been attached to these by the devices of vain mathematicians and by the blind vision of popular philosophers." [7].

Perfected by Ptolemy in the Almagest and in the Hypotheses planetarum, the system of the spheres (and epicycles) has been the foundation of the standard vision of the world for centuries. It accounts for the celestial movements of the stars with good precision. It also gives a cosmological basis to anthropology and ethics, extending the "scientific" representation into an answer to the question about being-in-the-world. That world would collapse under the deadly blows of the *De Revolutionibus Orbium Coelestium* by Nicolaus Copernicus.

4 The Copernican Revolution

In fact, canon Copernicus was not a revolutionary. His inspiration and his cosmological principles were strongly linked to the traits of Aristotelianism described above: they are the perfection of circular movements but also the finiteness and the spherical shape of the universe and the solidity of the crystalline spheres. And more than observing the sky, Copernicus, as a good humanist, sought his sources in the classics: "…I began to be annoyed that the movements of the world machine, created for our sake by the best and most systematic Artisan of all, were not understood with greater certainty by the philosophers, who otherwise examined so precisely the most insignificant trifles of this world. For this reason I undertook the task of rereading the works of all the philosophers which I could obtain to learn whether anyone had ever proposed other motions of the universe's spheres than those expounded by the teachers of astronomy in the schools. And in fact, first I found in Cicero that Hicetas supposed the earth to move. Later I also discovered in Plutarch that certain others were of this opinion." [8]. In fact, the Copernican revolution which "places the Earth as mobile and the Sun, on the other hand, as immobile at the center of the universe, is based on exactly the same astronomical data of the *Almagestus*.[5] There was nothing new under the Sun (nor above). Except that once the Earth is removed from the center of the universe, a question that we thought was decided comes back strongly: what is gravity?

[5] And also on the astronomical data transmitted by the Arabs. Albategnius and some other Arab astronomers are quoted by Copernicus.

Until recently it was believed that the *De revolutionibus* was already completed in 1530. Today it is known that the sixth book was written only after 1539. Four hundred copies were printed only in 1543, shortly before the author's death. The initial print run was not sold out. The text is preceded by a preface written anonymously by Andreas Osiander who had been commissioned by Georg Rheticus, the author of the *Narratio prima* [9], to oversee the publication of the book. Osiander was a former Catholic priest turned Lutheran theologian, very active and vaguely heretical. By professional deformation, he saw rather well the risks inherent in the theses of Copernicus, theses that undermined the scientific bases of the cosmic order that philosophy and theology conceived as anthropocentric. To counter these risks, Osiander, in his anonymous preface *To the Reader Concerning the Hypothesis of This Work*, repeats in even more drastic terms Posidonius' arguments:

"Since the novelty of the hypothesis of this work has already been widely reported, I have no doubt that some learned men have taken serious offence because the book declares that the earth moves, and that the sun is at rest in the center of the universe; these men undoubtedly believe that the liberal arts, established long ago upon a correct basis, should not be thrown into confusion. But if they are willing to examine the matter closely, they will find that the author of this work has done nothing blameworthy. For it is the duty of an astronomer to compose the history of the celestial motions through careful and expert study. Then he must conceive and devise the causes of these motions or hypotheses about them. Since he cannot in any way attain the true causes, he will adopt whatever suppositions enable the motions to be computed correctly from the principles of geometry for the future as well as the past. The present author has performed both these duties excellently. For these hypotheses need not to be true nor even probable. On the contrary, if they provide a calculus consistent with the observations that is enough." [10].

A computational hypothesis, which concerns only mathematicians, that's all. Revolution is something different!

Yet, the revolution was secretly underway. On the evening of November 11, 1572, leaving his uncle's underground alchemical laboratory and looking towards the zenith, Tycho Brahe, the greatest ever observer of the sky with the naked eye, saw a "nova et nullius ævi memoria prius visa Stella," a new star, brighter than Venus, in the constellation of Cassiopeia. It was unheard of! He doubted his vision and asked the peasants who were passing by if they saw the same star as him in the sky. This event would change the life of Tycho who became the first of the modern astronomers. The Stella nova was there to destroy the idea of immutability of the heavens, because there were changes in the superlunary world. Stars could be born and perhaps die …

After that, it was the turn of the crystalline spheres to break apart under the blows of the great comet of 1577. Tycho observed it for several months; the parallax of the comet allowed him to decide a thousand-year-old question: the comets were indeed celestial bodies. "All the comets which I have observed move in the ethereal region of the world and never in the sublunary region as Aristotle and his followers wanted us to believe for many centuries!" And as its trajectory, which was not at all circular, went through the orbs of the planets "the reality of crystalline spheres must be excluded from the heavens." The spheres do not really exist, the sky is free, open in all directions and there is no obstacle to the race of the planets. But, once destroyed the crystalline spheres *a quo moventur planetae*? What is the cause of the motion of planets and other celestial bodies?

Finally, the last to dissolve was the circular motion of the planets, already undermined by the superlunary comets. It is all the more ironic that the main motivation of Copernicus' work was to reestablish the perfection of the circular and spherical geometry. However, the astronomical data that Tycho had entrusted to Johannes Kepler and that Kepler had been studying hard for six years, said something else: the orbit of the planet Mars was not circular, nor reducible to a composition of circles, but it was an ellipse with the Sun at one of its focuses. Kepler wrote the *Astronomia Nova, αιτιολοητος seu physica coelestis, tradita commentariis de motibus stellae Martis ex observationibus G.V. Tychonis Brahe*, a book that since 1609 marks forever the history of astronomy. Yet the planetary ellipses were to remain a dead letter for a long time. It is only after Newton's law of universal gravitation that everybody accepted the Keplerian orbits of the planets. Today they still remain elliptic (roughly!)

5 The Galileo Affair

The *Astronomia Nova* was unlucky to appear shortly before the publication of Galileo's *Sidereus Nuncius* (1610). The Galilean heavenly messenger announces the revolution in broad daylight. He reveals that the Copernican point of view is not just a technical question for mathematicians but concerns everyone. Since then, the Galileo affair has been one of the most significant events in the history of western culture [11, 12]. Countless literary, philosophical and scientific books have supported virtually every possible stance regarding Galileo's condemnation, the relationship between science and religion, the birth of modern science and the scientific method. We are going to mention here only the few aspects that are relevant for our cosmological tale.

Galileo propagated the revolution by means of a canon-shaped telescope—the *cannocchiale*. This Dutch-made instrument was originally an object for the amusement of the wealthy. Galileo perfected it obtaining a much better magnification and sold it to the Senate of Venice as a military instrument.

Then, on the evening of August 25, 1609, he pointed his perfected telescope towards the sky and discovered a world that no one had ever seen. He observed the lunar landscape with mountains and valleys and myriads of stars of the Milky Way. On January 7, 1610, he observed three stars near Jupiter and then, on January 13, a fourth one. Their positions had changed: they were circling around Jupiter as everyone could see. Freed from verbose debates ("e noi liberati da verbose discussioni") the millenary conception of an unchanging and perfect sky that revolves around the Earth was over. Six and a half years later, on March 5, 1616, Copernicus' *De Revolutionibus orbium coelestium* was added to the Index, sixty-three years after its publication.

All of this is well known. But there is something here that must not escape our post-modern eyes. Today, Galileo's gesture of observing the sky with his *cannoc-*

chiale may seem obvious and even obsolete, but it was not at all so in his epoch and for many reasons. First there was nothing to see in the sky. Everything had to go as it had always been. Worse, the instrument used to observe the sky was unworthy, made by mechanicians and engineers, and therefore not very commendable for honest gentlemen and for academics (who often stubbornly refused even to touch the telescope).

It is by disregarding this official science that, with his solitary gesture, Galileo abandons the conception of the human natural senses as an absolute criterion of knowledge, and, trusting in what he sees through his instrument, lays the foundations of the scientific revolution that has forever changed the history of humanity.

Copernicanism is also the pillar of the project to establish a new science. The Copernican overturn of the cosmic order leads to the revolutionary idea that there is only one physics that governs the movements on Earth as in Heaven and opens the way for geometry to come down in our sublunary world to explain celestial and terrestrial phenomena on the same basis. Heaven, so to speak, descends to Earth (Fig. 1).

The most recent Galilean studies indeed point out how erroneous it would be to separate Galileo's researches on the movement and the fall of massive bodies—made in Pisa from the 1580s and in Padua thereafter—from his subsequent astronomical studies. These studies had already led him to reject scholastic physics. Aristotle taught, for example, that a body weighing ten pounds falls from a certain height in ten times less time than a body weighing one pound. Legend has it, that the young Galileo climbed the tower of Pisa and, at the passage of the academic procession, dropped the two weights that arrived on the ground almost at the same time. Experimental evidence had never been sought for before. It was an absolute novelty of the new Galilean scientific method.

In the bitterness of his old age, the prisoner Galileo had nevertheless the courage to go back to the study of free fall and the movement of the projectiles, in the third and fourth parts of his last book, *Discorsi e dimostrazioni matematiche intorno a due nuove scienze* (1638). "La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi a gli occhi (io dico l'universo), ma non si può intendere se prima non s'impara a intender la lingua, e conoscer i caratteri, ne' quali è scritto. Egli è scritto in lingua matematica, e i caratteri son triangoli, cerchi, ed altre figure geometriche, senza i quali mezi è impossible a intenderne umanamente parola; senza questi è un aggirarsi vanamente per un oscuro laberinto."[6] [13].

[6] Philosophy is written in this grand book, which stands continually open before our eyes (I say the 'Universe'), but can not be understood without first learning to comprehend the language and know the characters as it is written. It is written in mathematical language, and its characters are triangles, circles and other geometric figures, without which it is impossible to humanly understand a word; without these one is wandering in a dark labyrinth.

Fig. 1 Albrecht Dürer: *Melancholia I* (1514). Geometry comes down to Earth from the Skies. The wings of the angels are now useless…[14]

To better appreciate the greatness of this last work, we must remember that in the seventeenth century geometry had nothing to do with physics in the sublunary world (Fig. 1). Even the eminently practical problem of calculating the trajectory of a projectile posed by the new techniques of artillery, was approached by compulsorily studying the Physics of Aristotle to find the correct way to compose violent movements with natural movements (Fig. 2). In this context, it is possible to understand the novelty and importance of the experimental works of the young Galileo and of the Discorsi of his maturity where he shows that the trajectory of a projectile is a parabola resulting from the composition of two movements that do not interfere with each other: a straight horizontal motion in accordance with the principle of inertia and a uniformly accelerated vertical motion whose acceleration does not depend on the mass of the body.

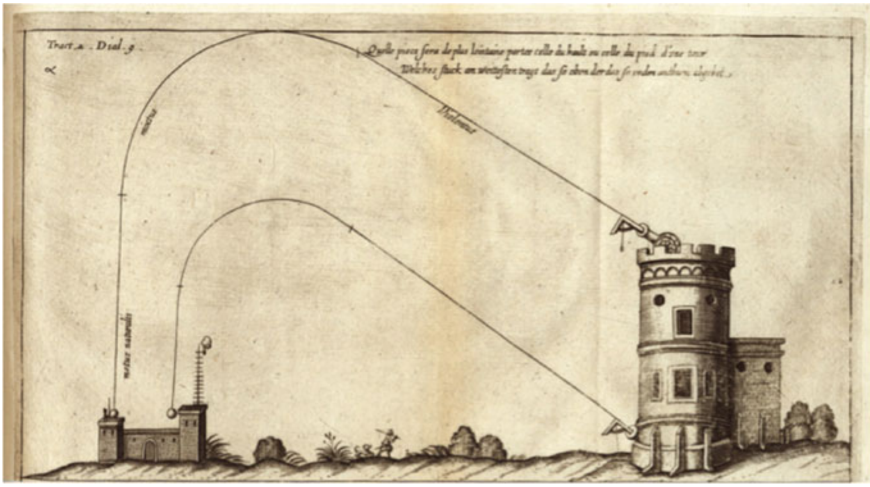

Fig. 2 Diego Ufano: *Artillerie (1628)*

The principle of equivalence of Galileo stating that all bodies fall (in void) with the same acceleration is, perhaps, the most important result of Galileo's new experimental science. It contains the germ of an answer to the questions about the nature of gravity and its universality (it is universal because it acts in the same way on all things and because it founds every science of the universe—including Aristotle's cosmology!) But this (provisionally) definitive answer will not come until three centuries later. Meanwhile Galilean science will find its climax and its accomplishment in the work of the greatest man of science ever: Isaac Newton (Fig. 3).

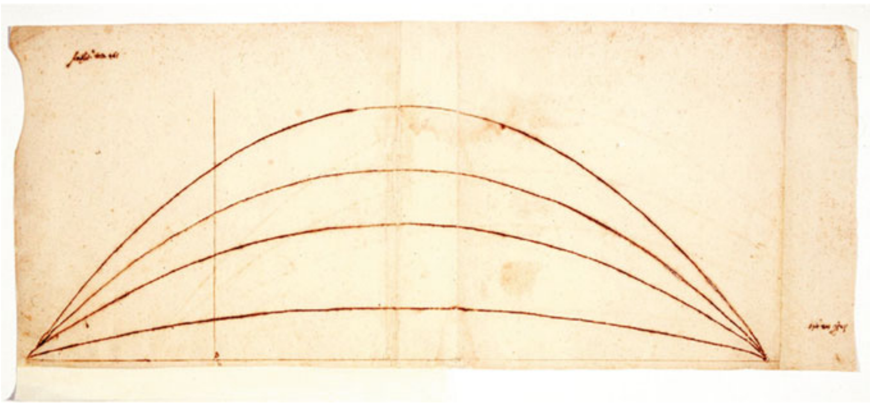

Fig. 3 Galileo Galilei. Codex 72. Folio 42 r. Galileo's new geometric theory of movement applied to ballistics