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Editors

The Universe

Poincaré Seminar 2015

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Foreword

This book is the seventeenth in a series of Proceedings for the *Séminaire Poincaré*, which is directed towards a broad audience of physicists, mathematicians, and philosophers of science.

The goal of the Poincaré Seminar is to provide up-to-date information about general topics of great interest in physics. Both the theoretical and experimental aspects of the topic are covered, generally with some historical background. Inspired by the *Nicolas Bourbaki Seminar* in mathematics, hence nicknamed *"Bourbaphy"*, the Poincaré Seminar is held once or twice a year at the Institut Henri Poincaré in Paris, with written contributions prepared in advance. Particular care is devoted to the pedagogical nature of the presentations, so that they may be accessible to a large audience of scientists.

This new volume of the Poincaré Seminar Series, **The Universe**, corresponds to the twentieth such seminar, held on November 21, 2015, at Institut Henri Poincaré in Paris. Its aim is to provide a description of some of the main active areas in astrophysics from the largest scales probed by the *Planck* satellite to massive black holes which lie at the heart of galaxies and up to the much awaited but stunning discovery of thousands of exoplanets.

The first article, entitled *The Big-Bang Theory: Construction, Evolution and Status*, by the distinguished theoretical astrophysicist, JEAN-PHILIPPE UZAN, formerly Deputy Director of the Institut Henri Poincaré, is a review of the modern cosmological model. The introduction underlines the fundamental role played by general relativity in the genesis of the Big-Bang paradigm. The author carefully explains the hypotheses and principles on which this scenario relies. The first main part of the review, entitled 'The construction of the hot Big-Bang model', then describes the various stages in the development and confirmation of the Big-Bang paradigm from pure general relativity to the inclusion of matter and the description of large scale structures. It presents its two historical pillars, primordial nucleosynthesis and cosmic background radiation. The analysis leads to the conclusion that our universe started in a very dense and hot phase at thermal equilibrium, followed by cooling due to its expansion. Other critical aspects of the model include dark matter, dark energy and the formation of large-scale structure arising from tiny inhomogeneities in the early universe. This part ends with a detailed discussion of the status of the current standard cosmological model, namely the Λ-CDM (Lambda Cold Dark Matter) model, in which surprisingly only six basic parameters are needed to analyze and interpret all observational data. In the second half, entitled 'The primordial universe', the author turns to an in depth analysis of the current scenarios for the early history of our universe. The main concept is that of *inflation*, namely an early phase of accelerated expansion of space which can solve some of the main problems of the hot Big-Bang model. In particular, it smoothes out inhomogeneities, anisotropies and curvature and it causally connects distant regions of the universe as observed today. Beyond this, it predicts the existence of small inhomogeneities of quantum origin which explain the observed temperature anisotropies of the cosmic microwave background and are the seeds of the large scale structure of the universe. Although there is nowadays some consensus on the inflationary scenario, many details and questions remain to be understood, which the author discusses carefully, at some point meeting the unsolved problem of quantizing gravity. In this form, the contemporary cosmological models explain the origin and diversity of the atomic nuclei and of large scale structure and give some hints on the origin of matter. After having summarized the history and main successes of the Big-Bang theory, as well as its remaining problems and open questions, the review looks forward to the discovery of gravitational waves. The first observation of these waves in September 2015 opens a new observational window on our Universe.

The second article, entitled *The Planck Mission and the Cosmic Microwave Background*, is written by JEAN-LOUP PUGET, from the Institut d'Astrophysique Spatiale in Orsay. Launched on 14 May 2009, the *Planck* satellite was designed to orbit the L2 Lagrange point of the Sun-Earth system, and map the sky in nine frequencies using two state-of-the-art instruments: the Low Frequency Instrument (LFI), which includes three frequency bands in the range 30–70 GHz, and the High Frequency Instrument (HFI), which includes six frequency bands in the range 100–857 GHz. The latter's design was the most ambitious, with better sensitivity and angular resolution, but also more risky since it used cryogenically cooled bolometers at 100mK. J.-L. Puget, HFI's Principal Investigator, explains in great detail the historical path, both theoretical and experimental, that led to the *Planck* project and its specific and successful design. It was the third generation space mission after COBE and WMAP, with a stronger emphasis on the polarization of the CMB which is a much weaker signal than the temperature one (by a 50 to 100 factor), and seven of *Planck*'s nine frequency channels were equipped with polarization-sensitive detectors. In the end, *Planck* worked perfectly for 30 months, about twice the span originally required, and completed five full sky surveys with both instruments, before being turned off on 23rd October 2013.

The temperature and the polarization of the CMB shows minuscule fluctuations across the sky, which reflect the state of the cosmos at the time when light and matter parted company, 380 000 years after the Big Bang. This provides a powerful tool to estimate in a new and independent way parameters such as the age of the Universe, its rate of expansion (the Hubble constant) and its essential composition of normal matter, dark matter and dark energy. One main objective of the *Planck* mission was the most precise determination and constraint of the Λ-CDM cosmological model parameters, and the article explains the spectacular reduction of errors brought in by the *Planck* data release of 2015, by using jointly the CMB temperature and polarization spectra, the gravitational lensing signals, as well the final improvement brought in by observation data from galaxy surveys (such as Baryon Acoustic Oscillations). The pattern of acoustic oscillations in temperature and polarization power spectra implies an early Universe origin for the fluctuations, as in the inflationary framework of the Λ-CDM model. The primordial fluctuations are found to be Gaussian to an exceptional degree. There are no gravitational waves found at the 5% level, suggesting the energy scale of an inflationary epoch was below the Planck scale.

Planck's polarization data not only confirm and refine the details of the standard cosmological picture determined from the measurement of the CMB temperature fluctuations, but also help answer fundamental questions such as when the first stars began to shine. As their light interacted with gas in the Universe, atoms were gradually split back into electrons and protons during the 'reionization epoch'. The liberated electrons once again collided with the light from the CMB, albeit much less frequently in the expanded Universe, still leaving a telltale imprint on the polarization of the CMB. In 2016, a new analysis of the highly sensitive polarization measurements from *Planck*'s HFI, improving on earlier results from LFI in 2015, demonstrated that reionization was a very quick process, starting fairly late in cosmic history and having half-reionized the Universe by the time it was about 700 million years old.

The extraordinary wealth of high-quality data the mission has produced continued to be scientifically explored, see `https://www.cosmos.esa.int/web/Planck`. After completing a new processing of the data, the final *Planck* collaboration 'Legacy' results have been released on 17 July 2018, under the general title *Planck 2018 results*, and comprise twelve magnificent pieces; the first one, *Overview and the cosmological legacy of Planck*, is highly recommended and can be found at `https://www.aanda.org/articles/aa/full_html/2020/09/aa33880-18/aa33880-18.html`.

The importance of the results of the ESA Planck Scientific Collaboration for the Human scientific enterprise cannot be overstated: in addition to ten previous awards, including the 2017 Émilie du Chatelet Prize from Société française de Physique awarded to François Bouchet, IFI's Deputy PI, and in Year 2018 only, the Royal Astronomical Society presented the Planck Team with the 2018 Group Award, the same team and the PIs of LFI (Reno Mandolesi) and HFI (Jean-Loup Puget) were awarded the 2018 Gruber Cosmology Prize, Jean-Loup Puget received the 2018 Shaw Prize in Astronomy, and the 2018 Marcel Grossman Institutional Award went to the Planck Scientific Collaboration (ESA), represented by Jean-Loup Puget!

The third contribution, entitled *Massive Black Holes: Evidence, Demographics and Cosmic Evolution*, is due to REINHARD GENZEL, who leads the Max-Planck Institut für Extraterrestrische Physik (MPE) in Garching. He shared the 2020 Nobel Prize in Physics with ANDREA GHEZ from the University of California at Los Angeles *"for the discovery of a supermassive compact object at the centre of our galaxy"*, alongside ROGER PENROSE from the University of Oxford *"for the discovery that black hole formation is a robust prediction of the general theory of relativity"* (see `https://www.nobelprize.org/prizes/physics/2020/press-release/`). Obscured by thick clouds of absorbing dust, the closest supermassive black hole (MBH) to the Earth lies 26 000 light-years away at the center of our Galaxy, associated with the compact radio source SgrA*. It has a mass four million times that of the Sun, is surrounded by a small group of stars orbiting around it at speeds which can be relativistic. R. Genzel describes in exquisite experimental details the key difficulties of making very high angular resolution observations of the motion of the stars. The Schwarzschild radius of a 4 million solar mass black hole at the Galactic Center subtends a mere 10^{-5} arc-seconds, corresponding to about 2 cm at the distance of the Moon. The breakthrough came from the combination of Adaptive Optics techniques with advanced imaging and spectroscopic instruments, that allowed diffraction limited near-infrared spectroscopy and imaging astrometry with a precision of a few hundred micro-arc-seconds in the last decade. Using the Very Large Telescope (VLT) of the European Southern Observatory (ESO) in Chile, the group at MPE led by R. Genzel, and a group at UCLA led by A. M. Ghez with the Keck telescope in Hawai, independently found that the stellar velocities follow a 'Kepler' law as a function of distance from SgrA* and reach within the central light-month more than 10^3 km/s. By 2016, the two groups had determined individual orbits for more than 40 stars in the central light-month. The most spectacular of these stars, called S2, is in a highly elliptical orbit with a 16 year period. These orbits show that the gravitational potential indeed is that of a point mass centered on SgrA*, and concentrated well within the peri-approaches of the innermost stars, at 10-17 light-hours or 70 times the Earth orbit radius, and about 1000 times the event horizon of a 4 million solar mass BH. Combined with a proper motion limit of SgrA*, this lead to the inescapable conclusion that it can only be a MBH, eliminating astrophysical alternatives such as clusters of neutron stars, stellar black holes, or brown dwarfs.

The extreme gravitational field provided by the supermassive black hole makes it the perfect place to test Einstein's general theory of relativity. Finally, on July 26, 2018, it was announced that observations of the Galactic Center team at the MPE have for the first time revealed the relativistic effects on the motion of a star passing near the central MBH in the Milky Way. The exquisitely sensitive GRAVITY and SINFONI instruments in the VLT Interferometer allowed them to follow the star S2 as it approached the black hole during May 2018. At the closest point, the star was at a distance of only 17 light-hours, less than 20 billion kms from the MBH (120 times the Earth-Sun distance, and 1.5 10^3 times its Schwartzschild radius) and moving at a speed of almost 8000 km/s, about 2.5 % of the speed of light. The new measurements clearly reveal the gravitational redshift of the star's light, with a change in wavelength in precise agreement with Einstein's theory. The team used SINFONI to measure the velocity of S2 towards and away from Earth and the GRAVITY instrument to make extraordinarily precise measurements of the changing position of S2. With a gain of 15 in resolving power and precision, GRAVITY creates such sharp images that it can reveal the motion of the star from night to night as it ‘grazes’ the black hole — 26 000 light-years from Earth. This long-sought result represents the climax of a 26-year-long observation campaign using ESO’s telescopes in Chile. (See http://www.mpe.mpg.de/6930756/news20180726.)

This volume ends with the thoroughly detailed contribution of Arnaud Cassan, a young astrophysicist at the Institut d’Astrophysique de Paris, entitled *New Worlds Ahead: The Discovery of Exoplanets*. This fascinating subject has developed at an ever accelerating rate since the identification of the first extrasolar planet in 1995 by Mayor and Queloz. We now have several hundred identified planetary systems with several thousand examples of exoplanets. The first part reviews all detection methods (pulsar timing, Doppler spectroscopy, transits, gravitational lensing, direct imaging and astrometry) with their respective advantages and limitations. The second part focuses on the astonishing diversity of planets and systems discovered, from the now famous hot Jupiters to super earths, from brown dwarves to planets orbiting pulsars. It implies a complete overhaul of our traditional Solar System paradigm.

The progress is so fast that it is difficult to catch up in this field. Since Cassan’s paper, discoveries of Earth sized planets, some of them in the habitable zone of their parent star, have added to the excitation. Such Earth-like planets are as close as *Proxima Centauri b* (four light-years) or *Trappist 1* (*seven* earth-size rocky planets only about forty light years away, three of them possibly harboring liquid water). Science fiction now pales in light of reality. The first signs of exobiology may no longer be far off, as Cassan concludes that the field of exoplanet research has opened a door to the unknown.

This book, by the breadth of topics covered in both the theoretical description and present-day experimental study of the Universe, should be of broad interest to physicists, mathematicians, and historians of science. We further hope that the continued publication of this series of Proceedings will serve the scientific community, at both the professional and graduate levels. We thank the Commissariat à l’Énergie Atomique et aux Énergies Alternatives (Direction des Sciences de la Matière), the Daniel Iagolnitzer Foundation, the École polytechnique, and the Institut Henri Poincaré for sponsoring this Seminar. Special thanks are due to Chantal Delongeas for the preparation of the manuscript.

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Séminaire Poincaré XX

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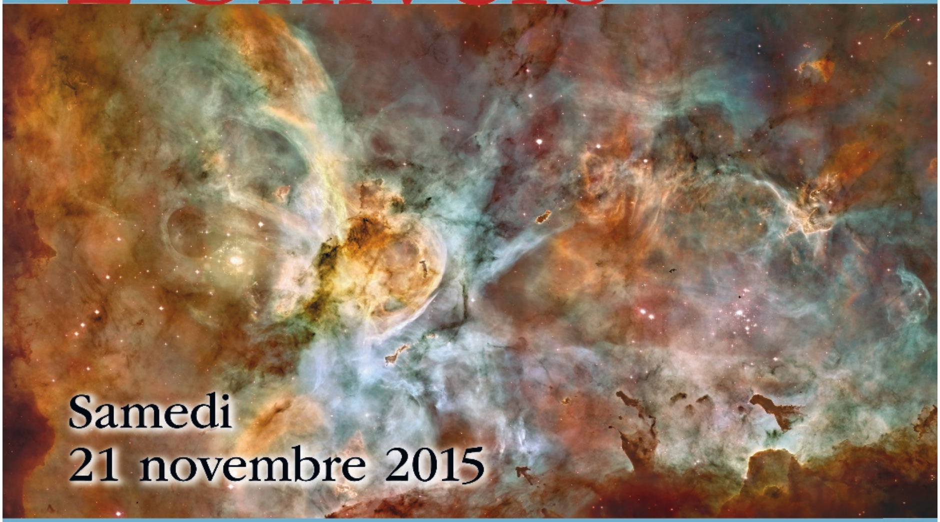

Samedi
21 novembre 2015

J.-P. Uzan : La théorie du Big Bang • *10h*

J.-L. Puget : Planck et le fond cosmologique • *11h*

R. Genzel : Massive Black Holes and Galaxy Evolution • *14h*

Y. Mellier : Les grandes structures de l'Univers • *15h*

A. Cassan : Les exoplanètes • *16h*

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