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Understanding the Dark Universe

Foreword

The Universe and its contents are still puzzling physicists and astrophysicists more than 70 years after Zwicky proposed the existence of Dark Matter and 10 years after the measurement of the Hubble diagram of distance type IA supernovae, which suggested the presence of Dark Energy. This recent discovery led to three Nobel prizes in 2011 although the physics of Dark Energy is still more than mysterious. In essence, around 95% of the energy budget of the Universe is completely unknown and manifests itself only in astrophysical situations while remaining elusive in laboratory experiments. The recent discovery of the Higgs particle at the Large Hadron Collider (CERN) may give hope that a hint for Dark Matter particles may appear in the next few years. This is not guaranteed either.

This volume of the Comptes Rendus de l'Academie des sciences is dedicated to Dark Matter and Dark Energy. Dark Matter provides a simple explanation to the anomalous flattening of galactic rotation curves. Dark Energy justifies the fact that the recent Universe, at least for the last 6 billion years, has undergone a phase of accelerated expansion. Other indirect clues that both Dark Matter and Dark Energy must exist have been provided by the study of the large scale structure of the Universe and the Cosmic Microwave Background (CMB).

In their paper, P. Astier and R. Pain review the observational status of Dark Energy. Numerous probes have been used in the last 10 years, ranging from the initial supernova surveys to future missions like EUCLID. Observations have concentrated on the determination of the equation of state of the Dark Energy fluid so far. If this parameter, which measures the ratio between the pressure and the energy density of Dark Energy, were to be equal to -1, Dark Energy would correspond to a cosmological constant (as originally introduced by Einstein in his static and spherically symmetric model of the Universe). In this case, the Universe would eventually become an empty de Sitter space in the far future, where all matter would be infinitely diluted by the eternal expansion of the Universe. Future observations will also try to distinguish between Dark Energy which corresponds to a new type of matter in the Universe and the possibility that the acceleration of the Universe could be due to a modification of the laws of gravity on large scales. M. Kunz presents the way both Dark Energy, as a new fluid pervading the entire Universe, or modified gravity can be phenomenologically described. In particular, the growth of structure which will be probed by future galaxy surveys could give us precious clues and help distinguishing between these paradigms.

So far, a pure cosmological constant with an equation of state of -1 represents the simplest and most economical interpretation of all the known observations. This causes serious theoretical problems as presented by J. Martin who emphasizes all the aspects of the "Cosmological constant problem". In this article, the quantum problems associated with a cosmological constant are analysed. This puzzle could be solved if vacuum fluctuations did not gravitate. This logical possibility related to the Casimir effects and quantum tests of the equivalence principle is reviewed.

Modified gravity has a long and checkered history. In her article C. de Rham presents modern accounts which go well beyond the original Pauli–Fierz theory. It turns out that modified gravity models, due to the scalar polarisation of a massive graviton, involve scalar fields like most Dark Energy models; an intriguing twist which may imply that either in the Dark Energy or in the modified gravity guises, scalar fields may hold the answer to the acceleration of Universe.

Nevertheless, it is still logically plausible that Dark Energy is simply a figment of our theoretical imagination and that the acceleration of the Universe is simply due to the largely inhomogeneous nature of the Universe. Indeed, our knowledge of the Universe is only limited to a local patch around the Earth and nothing prevents the fact that the Copernican principle could be violated. If we happened to live in a special void inside the Universe, the observed acceleration of the Universe would simply be the apparent manifestation of large inhomogeneities on cosmic scale. This possibility is reviewed by C. Clarkson.

Perhaps a way to progress on the interpretation of Dark Energy will come from the concerted efforts to elucidate the nature of Dark Matter. While the present consensus is that Dark Matter is made of a new type of particles and a signature of new physics beyond the Standard Model (BSM), so far all dedicated experiments have failed to discover any sign of Dark Matter particles. In fact the vanilla model which was proposed in the 1980s is now close to being ruled out. The latter predicts that the Dark Matter candidate must have a mass in the GeV–TeV range and weak interactions, based on a relic density argument and the assumption that Dark Matter is produced thermally in the Early Universe. Among the possible

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BSM extensions which can accommodate for stable neutral massive and weakly interacting particles, two scenarios in particular have been investigated widely in the literature, namely Supersymmetry and Extra dimensions. These are reviewed by T. Tait and D. Hooper along with the various mechanisms which have been proposed to give the Dark Matter its observed relic density. Supersymmetric and Kaluza–Klein candidates are known in fact as 'Cold' Dark Matter (CDM), i.e. they thermally decouple when they are non-relativistic. For many years CDM appears to be supported by numerical simulations. However, recently several problems arose while comparing CDM predictions with cosmological observations and this has called for a thorough investigation of astrophysical evidence for Dark Matter, as discussed by J. Silk.

While many new theoretical directions have been explored during the last five years regarding the type of Dark Matter candidates that could exist, the last decade witnessed tremendous experimental progress, with world record limits set on the spin-independent elastic scattering cross section of Dark Matter particles with nucleons. Also new methods and detectors were proposed to detect Dark Matter directly in underground experiments. The status of past, present and future direct detection experiments is reviewed by E. Armengaud. Finally during the last few years, many hopes have been set in the prospect of detecting Dark Matter indirectly through the observation of anomalous X-ray, gamma-ray, radio, submillimetre, neutrino components. The latest advances in this field and the tremendous efforts performed to tackle the propagation of cosmic ray in our galaxy is reviewed with great details by P. Salati and J. Lavalle who also discuss the problematic of backgrounds and the difficulty that this generates in the discovery of Dark Matter.

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