EXPLORING PHYSICS OF UNIVERSE USING SPACE LABORATORIES

Nan Yu, Slava Turyshev, and Ulf Israelsson
Jet Propulsion Laboratory, California Institute of Technology

All physics phenomena, from the processes in the microscopic world of elementary particles to the structure and evolution of the Universe, are governed by a set of fundamental physics laws. Although gravitation is a critical part of our description of the Universe, its quantization and unification with the rest of fundamental forces of Nature remains a challenge. *Could it be that our description of the gravity, as described by the Einstein's general theory of relativity, is not adequate and also is at the root of modern cosmological challenges?* Perhaps this is an indication for new physics. Any such possibility would then likely lead to breakdowns of well-established physical foundations which can be probed through various precision measurements. In parallel with laboratory measurements of high-energy particle and nuclear physics, space-laboratory precision measurements will provide valuable and complementary knowledge in enriching our understanding of astrophysics observations by addressing the following questions:

Is Einstein Equivalence Principle exact? Einstein's Equivalence Principle (EP) lies at the foundation of modern physics and underpins special and general relativities. However, there are recent observational challenges that demand theoretical approaches beyond the standard models of gravity and cosmology. The new theories predicate a violation of EP at various levels. Space based EP experiments can improve EP tests by several orders of magnitude below 10^{13} – the current limit achieved in terrestrial laboratories. An experimentally confirmed violation will fundamentally change our understanding of modern physics and the Universe.

Do fundamental physics constants change with space and time? Many theories today rely on extra dimensions, which could lead to a variation of the cosmological scale factor with epoch. This fact could in term lead to a temporal and special variability of fundamental physics constants, which usually also implies a violation of EP and observable deviations from general relativity. While search for a variation in the gravitational constant G can be constrained by lunar and planetary ranging, space-time variations in fine structure constant α are best measured by precision clock comparisons, especially using very different gravity potentials in space.

What is the nature of gravity and space-time at different scales? Given the immense challenge posed by the unexpected discovery of the accelerated expansion of the universe, it is important to explore every option to explain and probe the underlying physics. Alternative theories of gravity predict deviations at various scales – from microns to the solar system scales. Currently, the most precise value for the fundamental measure of the existence of the scalar field, was obtained with the Cassini spacecraft at the level of γ-1=(2.1±.3)×10^{-5}. Dedicated gravity time delay measurements in the solar system can put the measurement precision to beyond 10^{-9}.

Is space-time truly isotropic? Both general relativity and the Standard Model rely on the Lorentz invariance, which postulates independence of the outcome on the speed and direction of the light source and observer. On the other hand, our universe does not appear to be symmetric based on the anisotropy of the cosmic microwave background. Together with the Standard Model Extension (SME) predicting violations of Lorentz invariance, the search for space-time anisotropy becomes more intriguing. Because of large velocities and control of relative orientations to stars and galaxies using space platforms, the anisotropy of the speed of light can be potentially measured to $1\text{x}10^{-19}$ or better. The precision of many parameters in SME can be significantly improved.

How is quantum mechanics connected to gravity? How to directly connect the quantum world to gravity is one of the most illusive and profound questions in modern physics. While attempts to develop a quantum gravity theory has led to various predictions of violations in modern physics, there have been also conjectures that gravity directly interact with a quantum system, resulting in observable quantum decoherence. Macroscopic quantum systems such as large atom-wave separation and zero-point mechanical system are now achievable. Taking advantages of microgravity and gravity variations will allow possible observation of gravity effects on quantum systems such as universality of free fall of the quantum wave functions and gravity decoherence.