Exploring Dark Energy and Gravity in Space Laboratories

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract:
Dark energy is one of the greatest mysteries in science today and holds the key to the understanding of cosmology and evolution of our universe, and the potential for discovery of new physics. While astronomical observations are capable of providing ever increased precision in characterizing the dark energy and its history, there is a strong need for understanding the very nature of dark energy. Precision space laboratory experiments provide opportunities for direct detection of dark energy as well as help addressing other outstanding science questions in the area of gravity including dark matter and gravitational waves. A confirmed direct detection of dark energy will lead to a fundamental shift in our understanding of gravity, fundamental physics and our universe, stimulating a wide variety of foundational research in cosmology and particle physics.

Science questions addressed

The greatest mystery in science today is dark energy. Dark energy constitutes ~69% of the energy and mass of the universe, yet we know do not know what dark energy is. Together with dark matter, more than 95% of the universe's constituents are only known indirectly.

Because of the significance of dark energy to the cosmology and evolution of our universe, and the potential for discovery of new physics, it is no wonder that dark energy is one of the eleven fundamental science questions to be answered in the new century in the 2003 NRC report [1]. It is well emphasized in NASA's science strategic plans [2] [3]. Indeed, in addition to the existing astrophysics observations, there are new missions being planned and developed, such as WFIRST [4] and Euclid [5]. With larger and better observation telescopes in the near future, the content and evolution of dark energy and dark matter will be better characterized through snapshots of the distribution of baryons over cosmological space-time. However, the nature of the dark energy, i.e., the underlying equation of motion, will not be clearly verified via better data or analysis techniques from astrophysical observations. Particularly, among various feasible dark energy models and their huge parameter space, the ability to constrain or discern different candidate theories is limited, due to uncertainties on the nature of the medium between stellar light sources and observatories, and to the fundamental ambiguity of reconstructing dynamics through few points in space-time [6].

What is dark energy? The nature of dark energy itself is obscure and completely unknown today. It could simply be Einstein's cosmological constant. Yet this poses a conundrum, because straightforward arguments from quantum field theory suggest that the cosmological constant should be more than one hundred orders of magnitude larger than what is observed and attributed to dark energy [7]. The solution to this so-called cosmological constant problem clearly lies outside the known realms of gravity (as described by the General Relativity) and the standard model of particle physics. Even well-studied extensions of the standard model, such as supersymmetry, fail to provide answers [8]. New physics yet to be discovered is needed and opportunities to discover its nature await us. The new physics could be unknown fields directly, or modifications of gravity which may also introduce new fields indirectly. New fields should be scalar fields with very light mass, coupling to the particles of the standard model with roughly the same strength as gravity, and interacting with normal matter [9] [10]. This interaction provides us with golden opportunities to search and detect the unknown force experimentally in space through precision measurements of gravity.

A discovery of the new field would fundamentally change our understanding of the natural laws of physics. The connection with fundamental physics is clear. The interaction between baryons and the dark energy will cause a violation of Einstein's equivalence principle (EEP) [11] [12] [13], which states that all objects fall at the same rate in the same gravitational field. EEP is one of the founding pillars of Einstein's theory of relativity [14], which governs the dynamics on the cosmological scales. A confirmation of dark energy detection or a violation of the equivalence principle will lead to a wide variety of foundational research in cosmology and particle physics.

Dark energy as a scalar field

Phenomenologically, an energy density in space-time can drive cosmic acceleration if it has an effective negative pressure, and is given a name "dark energy." The "standard cosmological model," ΛCDM, consists of a cosmological constant Λ, cold dark matter, and a flat universe [15]. The cosmological constant, which is essentially a measure of the energy density, has to be finetuned to yield a stable universe. The quest for an explanation of the cosmological constant, or a broader theoretical framework to describe dark energy, results in various theories that could drive the cosmic acceleration. In quantum field theory approaches, dark energy arises due to vacuum fluctuations, but the resulting energy density is up to 120 orders of magnitude larger than observed. In modified gravity models, GR is modified to encompass the cosmic acceleration without dark energy. The consistency of the speed of light and the speed of gravitational waves severely restricts the validity of numerous modified gravity models [16] [17]. In quintessence theories, a new scalar field is introduced to account for the cosmic acceleration. Contrary to the cosmological constant, the quintessence field can vary in space and time [9] [10].

There has been much activity recently both on the theoretical fronts [12] [18] [19] [20] [21] [22] [23] [24] [13] [25] and experimental activities [19] [20] [26] [27] [28] for understanding the dark energy as a new scalar field. It is well known that general relativity has been stringently tested without any sign of violation so far, both with solar system observations and laboratory precision measurements. Therefore, any new interaction and the resulting unknown forces from dark energy must be highly suppressed on solar system scale; otherwise, it would contradict various precision tests of general relativity that have been performed to date. Viable scalar field theories of dark energy achieve this suppression by making the interaction between normal matter and dark energy environment-dependent. The mechanism for doing this is called screening, and works by changing the coupling between matter and dark energy to be dependent on the local mass density or other environmental factors. Three general screening mechanisms have been proposed [23]. Chameleon screening increases the effective mass at high local mass densities, reducing the range of the fifth force [18]; Symmetron models undergo a symmetry-restoring phase transition at high densities decoupling the field from matter [22]; and Vainshtein screening such as in Galileon models depends environmentally on the kinetic energy of the field, effectively reducing their matter couplings [29].

In the Chameleon model, the effective mass of the field is large inside and near concentrated baryonic mass distributions, and thus the Compton wavelength of the field and the corresponding force is short ranged. Similarly, in the Symmetron model, the symmetry of the field is restored inside baryonic mass, resulting in a short-ranged force near the surface of the mass. Therefore, only the outer most shell of a large compact body experiences the fifth force. This is known as the thin shell effect, facilitating the screening mechanism. Small particles such as single atoms, however, are smaller than the Compton wavelength of the field and experience the full effect of the scalar field. Laboratory experiments are conducted to exploit this enhanced sensitivity by using cold atoms for probing new forces [19] [26] [27] [28] [30]. The results significantly constrain the parameter spaces of the Chameleon and the Symmetron models in a complementary manner to

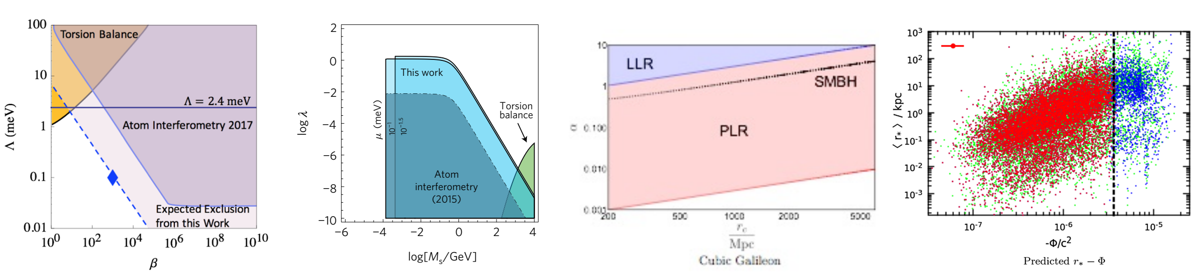

Figure 1. Recent progresses on constraints of scalar field models. From left: constraints on Chameleon [31], constraints on Symmetron [27], present (LLR) and future constraints on Vainshtein [13], and simulation on scalar field forces on astronomical observations [33].

bulk mass experiments and astronomical observations. Future microgravity experiment concepts could take advantage of better environmental controls and longer proximity time of atoms to a source mass available in microgravity, and it is anticipated that orders of magnitude improvement in sensitivity will confirm or rule out the models [31]. It is intriguing that recent observational studies suggest potential evidence of the thin-shell effect. The reported displacement of the centroids of hydrogen (H I) and stellar masses of galaxies, if confirmed, would be the first evidence of screening and possibly existence of a new scalar field [32] [33]. Figure 1 summarizes recent progresses on dark energy scalar field models.

The Vainshtein model, on the other hand, is difficult to constrain in research laboratory experiments due to their predicted weak long range force strength. An astrophysical constraint was reported [34], while recent multi-messenger gravitational wave detections suggest potential invalidation of Vainshtein models [16] [17] [35] [36]. Despite the weakness of the Vainshtein force, which is about 10^{10} smaller than gravitational force, a direct measurement of the Vainshtein field due to the Sun is shown possible in the solar system with modern precision measurement techniques in space [37]. Such measurements will be the first direct constraint placed on Vainshtein models and shed light on the models from an orthogonal perspective and complementarily to multi-messenger astronomy.

Enabling precision measurement advances

Since ancient times, astronomical observations have provided new insight on where we are and how Nature works. It remains one of the most powerful ways to explore and understand the universe. At the same time, to understand new fields and new interactions, high energy (accelerator) physics plays a crucial role to understand fundamental interactions and how the world is put together. However, the particle colliders can't probe gravity, while the next generation laboratory experiments can. Through ever increasing precision measurements that test interactions and dynamics predicted by the established laws of physics, laboratory precision measurements have the ability to seek small violations and probe physics at the Planck scale. In the last few decades, there has been an explosion of new technologies that provide exquisite tools for precision measurements. Highly accurate optical clocks for time and frequency measurements and atom interferometers for weak force measurements are two major breakthroughs out of these developments.

A continued program of testing fundamental physics would make unprecedented progress by moving to space laboratories, whether it is large gravity variation, large spatial extents, or speed and orientation. It turns out that clock and atom interferometer technology can benefit from operation on a space platform [38] [39]. In particular, atom interferometers use laser-cooled atomic particles as free fall test masses. It exploits the quantum nature of atomic particles as matter waves and forms matter-wave interferometers for sensitive inertial force measurements. The measurement sensitivity increases quadratically with the interaction time. With the possibility of many seconds of interaction times in space, very sensitive inertial force measurements can be made. Thus, conducting space laboratory precision measurements provides a unique ability to explore unknown physics, complementary to both the observational science in astronomy and accelerator science in high energy physics, and generates science data and knowledge that are not available from either observational or high energy physics measurements.

The atomic sensor technology has been demonstrated in research laboratories worldwide, commercialized for terrestrial applications, and matured for space deployment. In particular, the

Cold Atom Laboratory (CAL) is currently operating on the International Space Station as a multi-user facility, and serves as a pathfinder for future atomic sensors in space [40]. Moreover, the atom interferometer demonstration on a sounding rocket shows the robustness of atomic sensors [41] [42].

The inherent high sensitivity and stability of atomic sensors have been proposed, investigated and exploited for direct detection of dark energy, direct detection of dark matter, gravitational wave detections, and tests of EEP, among many other physics measurements. For instance, Chameleon and Symmetron dark energy models are tested and constrained using cold Cs and Rb atoms at University of California at Berkeley and Imperial College, UK, respectively [26] [28]. Dark matter measurement concepts are proposed using cold atoms in space [43] [44] [45]. Cold-atom based EEP tests are conducted [46] [47] [48] [49] and proposed [50] [51]. Note that, while the MICROSCOPE mission placed a bound on EEP at the 10^{-14} level using bulk masses [52], atomic tests at or beyond the current limit will provide a quantum mechanical constraint that is fundamentally distinct from the classical counterpart. Last but not least, several gravitational wave detection schemes are proposed using ultracold atoms on the ground and in space [45] [53] [54] [55] [56] [57]. Figure 2 illustrates the state of the art on atomic sensing in space.

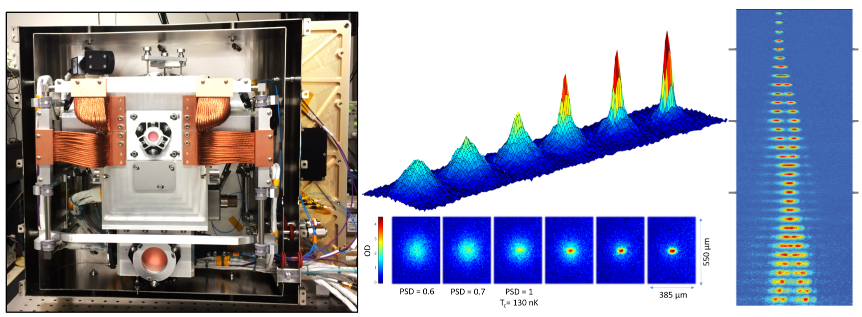

Figure 2. From Left: hardware of CAL on the ISS [40], BEC generation on CAL [40], and BEC interferometer in microgravity [59].

Science measurement opportunities

Led by the discovery of dark energy and dark matter, growing observational evidence points to the need for new physics aimed at answering important questions related to the most fundamental laws of Nature [58]. Efforts to discover new fundamental symmetries, investigations of the limits of established symmetries, tests of the general theory of relativity, detection of gravitational waves, and attempts to understand the nature of dark matter were among the topics at the focus of scientific research at the end of the last century. With the advances in precision metrology and gravity measurements, today, physics is standing at the threshold of major discoveries.

The fundamental physical laws of Nature are currently described by the Standard Model and Einstein's general theory of relativity. However, there are important reasons to question the validity of this description. Despite the beauty and simplicity of general relativity and the success of the Standard Model, our present understanding of the fundamental laws of physics has several shortcomings. In particular, if gravity is to be quantized, general relativity will have to be modified; however, the search for a realistic theory of quantum gravity remains a challenge. This continued inability to merge gravity with quantum mechanics together with the challenges posed by the discovery of dark energy indicates that the pure tensor gravity of general relativity needs modification or augmentation. It is believed that new physics is needed to resolve this issue.

Theoretical models of the kinds of new physics that can solve the problems above typically involve new physical interactions, some of which could manifest themselves as a violation of the

Equivalence Principle, variation of fundamental constants, modification of the inverse square law of gravity at various distances, Lorentz-symmetry breaking, or large-scale gravitational phenomena. The new interactions in turn introduce corrections to the current model of spacetime around massive bodies. Each of these manifestations offers an opportunity for experiment and could lead to a major discovery.

Space is one of the most likely places where these manifestations may be investigated. While providing access to greater variation of gravitational potentials, greater velocities, and full orientation coverage, space also extends the well-understood and controlled laboratory environments. These experiments have already been so successful on Earth and that the increased precision in space makes their discovery potential limitless.

In light of the advancement of dark energy theories, the encouraging indication of the screening effect due to dark energy scalar fields in astrophysics observations, and the maturation and potential of atomic sensor technologies, there is a strong motivation and justification for space laboratory science measurements in the coming decades that probe the dark energy field, the possible dark matter ultra-light field, and test fundamental physics laws. Complementary to what can be learned from future observational telescopes, dedicated space laboratories will enable stringent tests of dark energy models and possible direct detection of dark energy.

One possible mission concept is the Gravity Observation and Detection of Dark energy Explorer in Solar System (GODDESS) that comes out of a recent NIAC study [37]. The primary science objective is to detect the dark energy force sourced by the Sun as predicted by the Galileon model. The predicted galileon force is 10^{-10} smaller than the solar gravitational force at 1 AU distance away from the Sun. In the conceptual measurement scheme, a tetrahedral constellation of four spacecraft orbiting around the Sun measures the force gradients along the trajectory. Cold atoms onboard each spacecraft are used as test masses and quantum sensors, and laser ranging interferometers between the spacecraft measure relative displacements to yield force gradient. Gradient measurements are then combined to yield the force gradient tensor. The gravitational force, which follows the inverse-square law, has no divergence and contributes zero to the trace of the gradient tensor, and thus summing over the diagonal elements of the gradient tensor reveals the galileon influence. The trace measurement scheme completely mitigates the effects of the much stronger gravity backgrounds and allows the spacecraft to fly freely without the need for precise orbit control. A preliminary analysis shows that 3 years of continuous data collection in a 1 AU orbit around the Sun will detect the galileon force with a signal to noise of 3, based on the cosmologically observed Hubble's constant that governs the galileon model. Such a mission will not only constrain the galileon scalar field model, but also Chameleon and Symmetron fields.

Moreover, the tetrahedra constellation of precise differential gravity gradient measurements in GODDESS offers the opportunity to achieve other significant science objectives. The measurements from GODDESS would also provide rich and diverse scientific data for testing gravity field theories in general beyond Newtonian gravity, hunting for ultra-light fields of dark matter, as well as detecting gravitational waves in the mid band frequency spectrum between those of LIGO and LISA, as described in the NIAC report.

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