Gravity Probe and Dark Energy Detection Mission (GDM)

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1. Introduction

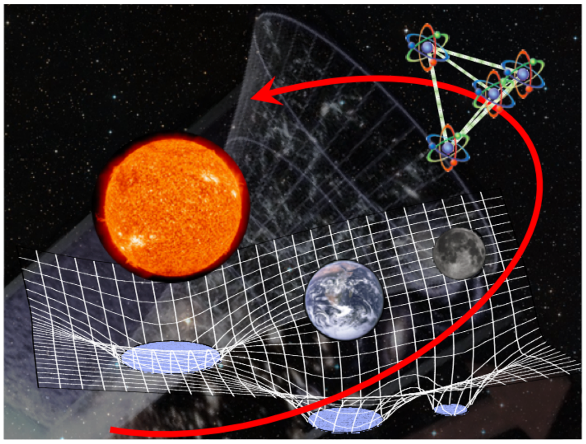

Figure 1. Illustration of the Gravity and Dark Energy Detection Mission concept. A tetrahedral constellation of satellites orbiting in an elliptical orbit around the Sun. Atom interferometers are operated outside the spacecraft in space vacuum for drag-free differential gravity measurements.

The Gravity probe and Dark energy detection Mission (GDM) concept is a proposed space experiment to directly detect dark energy in the solar system through measurements of deviations from the Newtonian $1/r^2$ gravitational field (Yu 2019). It would consist of four spacecraft in a tetrahedral formation, each carrying atom-wave interferometers, linked by high precision laser ranging between spacecraft (see Fig. 1). This would allow GDM to measure the gradients of the gravitational force in four directions simultaneously, and reduce the trace of the gravity field tensor in any orientation of the constellation. A non-zero trace would indicate a violation of the Newtonian inverse square law (ISL) and possible detection of dark energy as a scalar field. A confirmed direct detection of dark energy would 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. While the current GDM design is driven by the requirements for dark energy detection, GDM would also be capable of probing new parameter space in the search for dark matter, gravitational wave detection, and quantum gravity interactions.

2. Science Objectives

Dark energy & modified gravity

The nature of dark energy, the substance causing the accelerated expansion of the Universe, remains totally unknown. Over the next decade, several astronomical surveys and missions will collect increasingly detailed data about dark energy, its distribution, and evolution history. These missions include the Nancy Grace Roman Space Telescope (Akeson 2019), Euclid (Laureijs 2011), the Vera Rubin Observatory (Ivezi´c 2019, DESI Collaboration 2016), and SPHEREx (Doré 2014). While these surveys will help significantly improve our understanding of dark energy, it is expected that there will remain questions about the nature of dark energy after these surveys finish. GDM, a dedicated space mission within the solar system to directly probe dark energy, would provide a necessary complement to these astronomical surveys towards a total understanding of dark energy and its physics.

To date, dark energy has only been observed through its effects on galaxy positions, motions, and observed shapes; however, certain theories for dark energy would also have effects at closer distances. In particular, theories that explain dark energy by modifying General Relativity (GR) can have effects within the solar system (see Sakstein, 2018, for a recent review). These theories typically invoke 'screening' mechanisms, which make the theories to behave as GR close to large mass sources and only betray their true, modified properties at far distances. This allows these modified gravity theories to evade current solar system constraints. However, a sufficiently precise measurement of the gravitational acceleration as a function of radius within the solar system would be sensitive to these theories. GDM, armed with atom interferometer-based sensors for extremely precise acceleration measurement capabilities, would be able to detect these small deviations from Newtonian gravity.

The expected dark energy force is extremely small in the solar system because of the screening mechanisms. It is expected to be about at least ten orders of magnitude smaller than that of Newtonian gravity (Yu,2019, White 2020). To make the measurements robust against the much larger gravity field, GDM will focus on the gradient of the acceleration field. In particular, the trace of the gradient of a $1/r^2$ force vanishes for Newtonian gravity. This is not the case for any modified acceleration laws. Therefore, GDM seeks a violation of the ISL through a non-zero trace distribution in the solar system at a trace measurement sensitivity of $10^{-24}/s^2/Hz^{1/2}$.

Although this measurement will be theory agnostic, here we give some examples of possible theories and the constraints GDM would place on them. Often, fifth-force theories are described using a Yukawa potential: $V(r) = GM/r\,(1+\alpha e^{-r/\lambda})$, where α is the coupling constant and λ is the screening length of the theory, which corresponds to the inverse effective mass of the field. As shown in Fig. 2, after 3 years of observation GDM would place very competitive constraints at large screening lengths, compared to the current best limits. The constraints for two other screening mechanisms, Chameleon and Symmetron, are shown in Fig. 2 as well (where we define the model parameters as in Sakstein 2018).

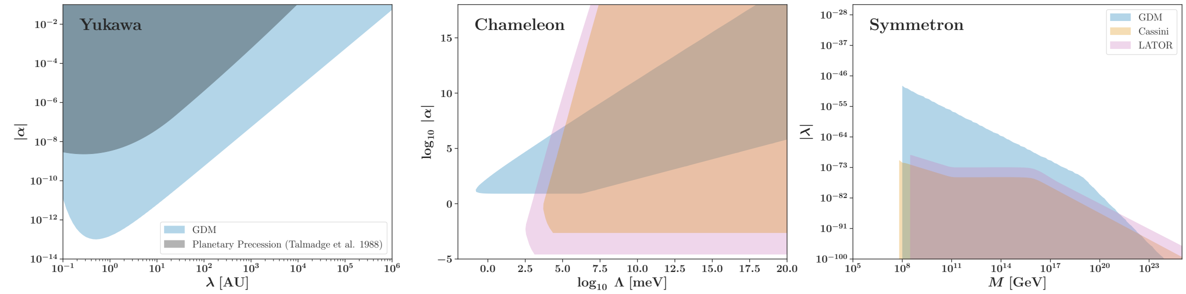

Figure 2. GDM forecasted limits on fifth forces and screening mechanisms in the solar system. The blue regions show the areas that GDM would be able to constrain with SNR > 5 after 3 years of observation, assuming an orbit at 1 AU. Left panel: Constraints on a Yukawa fifth-force, where the relevant parameters are the coupling constant, α, and the screening length, λ. The grey contour shows the existing constraints from planetary precession (Talmadge 1988). Middle panel: Constraints on a fifth-force with a Chameleon screening mechanism, where the relevant parameters are the coupling constant, α , and the mass scale of the field, Λ. The orange contour gives the constraints from the Cassini mission, and the pink contour gives the constraints from the proposed LATOR mission (see Sakstein 2018). Right panel: Constraints on a fifth-force with a Symmetron screening mechanism, where the relevant parameters are the coupling constant, λ, and the symmetron mass, M. The orange and yellow contours are as defined for the middle panel.

Gravitational Waves

Gravitational waves are a new way to observe the Universe, as demonstrated by LIGO's detection of gravitational wave signals. They provide us with unique tests of general relativity and the equations of state of compact objects. The tetrahedral constellation of GDM, with the equivalent of four two-arm interferometers, will be well suited for gravitational wave detections. With the currently defined constellation armlength of about 100,000 km and its atom interferometer accelerometer sensitivities, it would be capable of filling the gap in the $10^{-3} - 10$ Hz range between aLIGO (Harry & LIGO Scientific Collaboration 2010) and LISA (eLISA Consortium 2013). This would make it sensitive to the mergers of $\sim 100 - 1000\ M_{\odot}$ black holes (Fig. 3 and also see, for example, Dimopoulos 2019).

Interestingly, the non-planar multi-pair arms of GDM offer the possibility of cross-correlation measurements, which cannot be done with the LIGO or LISA configurations. The most sensitive techniques for searching for a stochastic gravitational-wave background involve cross-correlating signals from different detectors, since orthogonal polarizations of a stochastic background field will be statistically correlated. Stochastic background signals may be produced in the very early universe (when the universe was much less than one second old) and through the superposition of binary black hole inspirals throughout the universe. The latter has much larger amplitudes but we estimate that GDM should be able to disentangle them.

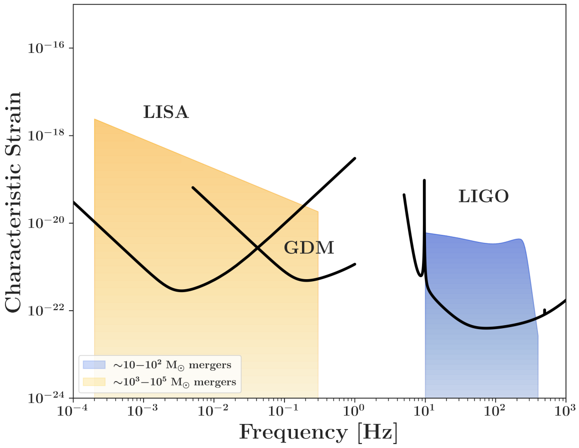

Figure 3. Gravitational wave sensitivities of LISA, LIGO, and GDM in the characteristic strain vs. frequency space. The colored regions show common gravitational wave sources.

Other Possible Science Measurements

Dark matter (DM), a substance that interacts with gravity but that does not seem to interact with any other Standard Model force, makes up most of the matter in the Universe. However, like dark energy, its nature is unknown. GDM could be sensitive to DM through its possible temporal change of fundamental constants (Arvanitaki 2018) or through decoherence induced by DM scattering (Riedel 2017).

Furthermore, GDM could help make progress in our understanding of the quantum nature of gravity. It remains unclear whether gravity is fundamentally a quantum entity or a classical one (Carney 2019). Conventionally, experiments probing the quantum nature of gravity were thought to be prohibitive due to the extremely high energy involved at the Planck scale. However, using novel quantum information-theoretic techniques, we can let the gravitational interaction act as a mediator to dynamically and decisively process quantum information. Quantum atomic systems in freefall in space may provide unique settings for some of the possible quantum gravity experiments (Singh 2021).

3. Mission Concept & Design

The GDM mission concept, formulation, and design are primarily driven by its requirements for the dark energy detection. We use the cubic galileon field as a measurement benchmark. It has been shown that the expected strength of a fifth force of this type is ten orders of magnitude smaller than that of Newtonian gravity. However, it has a strong distance dependence from mass sources, that is, spatial dependence in the Sun-Earth-Moon system (White 2020). The signal is strongest around the Sun, and it has a strong and unique spatial dependence that does not obey the $1/r^2$ law.

In order to robustly detect dark energy in the solar system, we consider the following key design points. First, we translate the extremely small fifth-force measurements into a non-zero gravity tensor trace measurement as mentioned before, thus strongly suppressing the larger Newtonian gravity signal. Second, we choose a tetrahedral constellation shape so that the gradient and trace measurements are independent of the orientation of the constellation relative to the source mass. Third, we choose an elliptical solar orbit, which would modulate a dark energy signal by at least a factor of two. This will help mitigate low frequency noise and provide the ability to map out a non-zero signal detection. While the tetrahedral formation can only be maintained for part of the orbit time without intervention, only small, frequent velocity kicks are required to maintain the formation throughout the elliptical orbit.

On the technology side, making the measurement drag-free is one of the most critical requirements. In order for this to happen in multiple directions on each spacecraft, atomic particles are used for the test masses. They are to be placed and operated in open space vacuum 100 m away from the spacecraft to reduce the spacecraft self-gravity gradient. This is drastically different from the approach of caging test masses used in the LISA mission (eLISA Consortium 2013). Operating atom interferometers in the vacuum of open space is new and can be susceptible to other effects of the deep space environment. A preliminary study of these effects in the current investigation has not found any significant concerns.

To reach GDM's required acceleration sensitivity of $1\text{x}10^{-14}$ m/s^2/Hz$^{1/2}$, each atom interferometer must have 10^8 participating atoms and remain compact for 20 s. An advanced cooling scheme is thus needed to provide 10^8 atoms at <1 nK. The interrogation time will be about 20 s. The most advanced large-momentum-transfer Bragg and Bloch oscillation atom interferometer protocols will be used (see for example, Gebbe 2021). The use of these atomic measurement approaches will also help maintain the measurement stability over long orbital periods around the Sun.

To operate atom interferometers outside of each spacecraft, we will need retroreflectors away from each spacecraft. Mechanical booms are too heavy and unstable. We plan to use free-flying cubesats with retroreflecting corner cubes co-flying with each main spacecraft. A preliminary study suggests that only a 3 m/s ΔV over five years is needed when the main constellation is allowed to drift.

In order to accomplish the gradient tensor measurements, the gravity gradients are measured between each pair of the four spacecraft, resulting in six pairs of differential measurements. For each pair of differential measurements, atom interferometer accelerometers on each spacecraft are coherently linked by laser ranging interferometers. The baseline separation is on the order of 100,000 km at 1 AU from the Sun. This baseline choice is constrained by the gradient measurement sensitivity required and the gravity gradient error due to the finite distance measurements. The long-baseline differential atom interferometer measurement scheme is described by Chiow et al. 2015. Indeed, one can think of this as a very long atom interferometer gravity gradiometer. The laser link would be similar to that in the LISA mission, except with a shorter baseline. As a result, the laser ranging system would use less laser power and the time-delayed interferometer scheme that LISA relies on will not be needed, given currently achievable laser stability. On the other hand, the measurement precision of GDM requires the tetrahedral formation to be very rigid, with absolute ranging measurement accuracy at the µm level over 100,000 km. This kind of ranging has not been done before, but is feasible, especially with optical frequency combs (Fortier 2019).

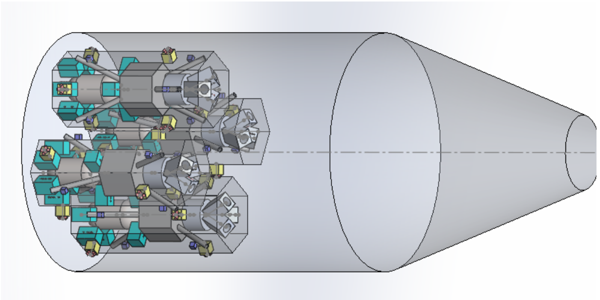

Figure 4. Concept of four spacecraft with their offspring satellites in a Falcon Heavy rocket fairing.

In the current GDM baseline configuration, four spacecraft will be co-launched on a Falcon Heavy for a solar elliptic orbit stretching from 0.5 AU to 1.5 AU. Each spacecraft will have three atom interferometer pairs and three optical interferometer payloads. A preliminary orbit simulation suggests that the tetrahedral constellation will need to be actively maintained to achieve the necessary inter-spacecraft pointing and gravity gradient measurement precision. This is quite feasible in the slow dynamic environment of the solar orbit. A more precise formation maintenance will significantly reduce the burden of the spacecraft attitude control and pointing, and at the same time, provide nearly 100% of the useful measurement time. In the current GDM design and requirements, GDM would achieve a 5-σ non-zero trace detection of a cubic galileon fifth force in three years. The same set of the measurement data can be used for gravitational wave signal and other science analyses.

4. Current Status and Roadmap

The GDM concept is currently a NASA NIAC Phase 2 study, with the main investigation focusing on the mission architecture and instrument design concept, measurement system requirements and error budgets, and technology maturation and gaps identification. From the mission design perspective, the main challenges are the deployment of four main spacecraft and maintaining the required formation of the offspring smallsat reflectors. Spacecraft attitude control to maintain precise laser linking also presents a technical challenge. There are a number of technologies used in the GDM instrumentation that also must be advanced, matured, and validated. Among them are high-sensitivity atom interferometers, the ability to operate cold atoms in the vacuum of space, and laser ranging with one part per 10^{14} absolute accuracy. On the science side, dark energy scalar field models must be further studied and matured. Currently, there is no single model, including the cosmological constant, that is consistent with all astrophysical observations and known fundamental physics laws. By the end of this decade, the currently planned dark energy surveys and projects will have provided us with dark energy's large-scale effects. However, we will be still left with important questions about the fundamental nature of dark energy. GDM is designed in anticipation of this next phase of dark energy investigation. GDM's measurements are model independent and can be used for testing any modified gravity models that can manifest in the solar system. We must be prepared to meet the new challenges beyond the current dark energy surveys, and GDM is one step in that direction. GDM will likely be in the large mission class, given the number of the spacecraft used. Significant investments are called for in both theoretical investigations and key technology maturations to help answer this key science question in Fundamental Physics.

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