Gravitational Wave Detection with Asteroids

There is a golden opportunity to use asteroids as test masses to probe gravitational waves and ultra-light dark matter in the microHz frequency range. At present, there are no agency supported missions in this frequency band. Terrestrial interferometers operate at frequencies above 10 Hz while pulsar timing arrays are focussed on the nHz band. The proposed LISA constellation will focus on the mHz range, while atom interferometric concepts such as MAGIS/AION are aimed at the frequency band 100 mHz - 10 Hz.

The science case for probing this frequency band is exceptionally strong. This frequency band features the mergers of supermassive black holes, some of the most violent events in the universe. These mergers are crucial to understanding the growth of structure in the universe - especially since current theories do not explain experimental observations of such supermassive black holes. The growth of structure is a key method to further investigate the equation of state of dark energy. It is also possible that these mergers might provide insight into the ultra-high energies of quantum gravity itself. It is generally believed that the Schwarzschild black hole describes the geometry of black holes. While this is undoubtedly true outside the horizon of the black hole, the black hole information problem raises considerable doubt if the interior of the black hole is governed by the predictions of General Relativity. Importantly, the Schwarzschild solution is not a “conservative” assumption - as matter collapses to form a black hole, General Relativity predicts that it will eventually hit a singularity - i.e. - a point where General Relativity breaks down. Beyond this point, we do not know how the solution evolves. The subsequent evolution of this system could be as predicted by General Relativity (which then leads to the Schwarzschild solution and the information problem) or it could easily lead to a dramatically different evolution resulting in the existence of Planck density physics at the horizon. If the latter case is true, gravitational wave observatories may actually enable the study of quantum gravity.

Ultra-light dark matter at the microHz frequency is particularly well motivated since it is close to the limit of “fuzzy” dark matter. Observational limits on the dark matter allow its mass to range from 0.1 microHz - 10^{24} gm. Dark matter in the microHz naturally explains observational puzzles such as the observed absence of the clustering of dark matter in the cores of galaxies since these kinds of fuzzy dark matter are too fluffy to fit into such a core. Moreover, from a theoretical perspective, such particles emerge naturally from theories such as string theory and generic initial conditions where we assume that the dark matter field starts at the Planck scale in the early universe. The detection of such dark matter particles would shed light not just on the nature of dark matter, but also on these long standing galactic mysteries and may permit insights into the highest energy scales of particle physics.

A detector that measures accelerations at microHz frequencies between two base-stations can be used to detect both gravitational waves and ultra-light dark matter. This measurement can be performed by sending radio waves from one base-station to the other and measuring the time of arrival of those radio waves by using a precise clock at the other base-station. Further, it is also necessary to ensure that the relative motion between the base-stations is only due to the gravitational wave or dark matter. To achieve interesting science one needs clocks with stability at the 0.1 fs level and control over the relative distance between the base-stations at the 0.1 micron level. Quantum sensors such as atomic clocks have surpassed this level of sensitivity, though none of them have been deployed in space. But, the 0.1 micron level control of the distance between the base-lines is challenging. This requirement imposes a stringent limit on the reach of detectors - terrestrial optical interferometry detectors such as LIGO are swamped by seismic noise below 10 Hz. Even a satellite mission such as LISA has to overcome the problem of the satellites suffering random motions due to the space-environment. While the LISA Pathfinder mission successfully demonstrated the necessary level of control at mHz frequencies, this level of control is well above the required levels at microHz frequencies.

The problem of creating a stable enough base-station can potentially be solved by focussing on the following aspect. A satellite that humans can launch has a mass in the few ton scale - the space environment is noisy enough to move objects of this size. A planet such as the Earth on the hand is massive enough that its center of mass is too heavy to be moved by the space environment. But the earth is big enough that it has its own atmosphere and seismic activity giving rise to fluctuations on its surface that are too large to host a base-station for low frequency accelerometry. We thus need objects that are large enough to have a stable center of mass while not being too large that they have intrinsic seismic activity. There are natural objects in the solar system that fit into this category - the moon and asteroids.

Measurements of the seismic activity on the moon from the Apollo missions indicate that the seismic activity levels are at the nm scale, low enough to permit the required microHz accelerometry. An asteroid such as 433 Eros (successfully visited by NASA) with a mass of ~ 10^{15} kg is massive enough that the space-environment will not cause its center of mass to jitter by more than 0.1 microns on relevant timescales. Seismic activity on these kinds of asteroids is also estimated to be small enough to permit detection.

There are two kinds of detector concepts that can be conceived. In the first, one can place a ~ 3m radio telescope on the moon and 433 Eros. Radio waves are sent between these and the time of arrival is measured using an atomic clock on each end. The experiment looks for the modulation in these arrival times for detection. Second, one may place a radio reflector on the surface of the moon and 433 Eros. Satellites that orbit both these bodies use these reflectors to ensure that the distance between them and the reflector does not change by more than 0.1 microns in the microHz frequency. The satellites then use radio dishes (of size ~ 3 m) to send radio signals to each other. Atomic clocks that are onboard the two satellites measure the time of arrival of these pulses and search for the modulation in these pulses at microHz frequencies.

The former concept is likely technically less challenging but suffers from duty cycle issues - the detector can operate only when there is a line of sight between the lunar surface and the asteroid. The latter concept is likely technically more challenging but would enable a longer duty cycle since the satellites can be in regular contact.

It is important to note that ~ 3 m radio dishes operating in the 100 W regime are necessary for this kind of mission. These appear to have been used in commercial satellites. The proposed mission is also similar in spirit to Lunar Laser Ranging - a concept that yielded terrific measurements of the equivalence principle for over 30 years.

It is interesting to note that the above mission concept builds on several existing NASA capabilities and is well aligned with other proposed mission goals. For example, NASA has already launched successful missions to asteroids. These include NEAR Shoemaker which orbited 433 Eros and OSIRIS-REx which performed a landing on 101955 Bennu.

Further, atomic clocks that are stable to 0.1 fs over micoHz frequencies are necessary for this mission. But there has not been a space-based demonstration yet. There is however considerable effort in the broader physics community to build space qualified atomic clocks that can operate robotically without human intervention. This includes efforts to operate such a clock on the ISS.

Given the strong science case for gravitational wave detection, there is considerable reason to explore viable technological options across the entire spectrum of gravitational wave frequencies. We believe that the above concept warrants further investigation by NASA.