Time Delay of Gravitational Waves Propagating Through a Galaxy Toward a Non-Stationary Observer and Other Problems

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The nature of dark matter is currently unknown, but with many candidate theories having been proposed. Any method of dark matter detection would allow us to differentiate between the available models of dark matter. To this end, we must learn what effect we expect the various models of dark matter to have on measurements. Takahashi [1] explored how a particular model of cold dark matter distributed inhomogeneously with various scale sizes resulted in both amplitude and phase fluctuations in a gravitational waveform arriving at Earth from a super-massive black hole merger. We originally intended to extend Takahashi's methods to apply to a more complete set of dark matter models, in particular to topological dark matter defects. This information could be used to determine the feasibility of detecting these models of dark matter using interferometric gravitational wave detectors such as LIGO and LISA. We were unable to solve these problems and instead made progress determining the expected observed gravitational time delay derivative of a gravitational wave being observed by an observer moving like the earth in the Milky Way. We estimate the maximal effect to be about 0.29 s/yr for distant sources (>20 Mpc). The effect is somewhat lesser for closer sources, and a typical effect would be about one third to one half of this value dependent on the direction of the source from the earth relative to the galaxy's mass distribution.

Topological dark matter defects could have occurred when nontrivial stable field configurations emerged from coherent oscillations about the minimum energy of various field's potential wells in early cosmological times [3]. Murayama and Shu estimate the distribution and density of such topological defects produced via the non-thermal Kibble mechanism [2]. Drawing on their work, we originally intended construct a model of the effect on the metric caused by topological dark matter defects which would allow us to proceed similarly to Takahashi in determining the amplitude and phase fluctuations caused by gravitational waves propagating through a region populated with these defects. We initially considered a model of the effect of dark matter domain walls on passing gravitational waves based on their having a separation of about 30 parsecs and the assumption that they are randomly and independently distributed [7]. Along with some other assumptions and approximations, we were able to estimate the expected phase deviation of the wave relative to it not having passes through the domain walls. Unfortunately for this model, it seems that a series of simulations [8,9,10] have effectively excluded domain walls as a candidate for either dark matter or dark energy in all but some rather exotic models, so we decided to turn our efforts to other problems.

Our primary result from this project was obtained in solving for the derivative of the observed gravitational time delay of the signal observed from a gravitational wave traveling through the Milky Way's mass distribution from a distant source. We used a simple approximation of a 1/r mass distribution up to a distance of 5*10^20 m with a total mass of 6*10^42 kg and the observer positioned 2.6*10^20 m from the center of the mass distribution, to approximate Earth's location in the universe. The computation of the expected effect was performed in Mathematica in a notebook which will be permanently hosted at http://goo.gl/9kJK9a. The method used was to parameterize a path from the distant source to the observer and integrate the gradient of the Newtonian potential along the parameterized path.

$$\Phi = \int \frac{M(r)}{r^2} dr \qquad g = \Delta\Phi \qquad \dot{t}_{delay} = \int v \cdot g \, dl$$

Using these formulas, we obtained values for the gravitational time delay derivative ranging between 0 and 0.29 s/yr dependent on the direction of the source from the observer relative to the provided mass distribution. This is a large enough effect that it is at least plausibly measureable.

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