Search for Drifting Constants via Extra-Galactic Alcohol

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Executive summary

The Big Question on the complexity in our Universe is connected to the specific values adopted by the fundamental constants of nature, specifically the coupling constants defining the strengths of the four known fundamental forces: electromagnetism, the weak force, the nuclear force, and gravity. These constants of nature exhibit an intricate interplay, known as “fine-tuning”. The specific values of the coupling constants in our Universe determine that protons are stable, that a set of > 100 elements exists, that galaxies can be formed, that stars can burn over extended time scales, that roughly equal amounts of carbon and oxygen elements are produced in the super-novae death of stars, and that complex molecules based on carbon can form. Possibly, these values only hold in our region of the Universe. In such case our Universe may be considered as part of a set of Multiverses, a second Big Question.

Physics has not provided an understanding as to why the constants of nature adopt certain values. While the complexity in the Universe relies on specific fine-tuned values of the fundamental constants, Universes with other sets of values could exist. Our set of values, however, seems to be crucial for a special Universe, special in the sense that they allow for complexity, for life, and for intelligent life. This special situation in physics and cosmology has been explained in terms of the Anthropic Principle: the notion that our Universe is special for the mere reason that intelligent life forms can study it.

Anthropic scenarios are metaphysical, rather than physical. Even though the program of physics may not find explanations for the values of the constants of nature, non-anthropic mechanistic explanations were put forward suggesting a cosmological scenario with an evolving Universe [Smo04]. In a mechanistic process of cosmological natural selection sequences of Multiverses are formed, ultimately evolving to a Universe where complexity arises. In such a scenario tiny variations in the fundamental constants are crucial ingredients. The search for tiny variations in the values of the fundamental coupling constants in the early stages of the Universe is therefore an operational approach to the Big Questions of complexity and Multiverses.

The possibility that fundamental constants of nature may vary in time, or may obtain different values in distinct parts of the (multi)-Universe, has become part of experimental science. Highly redshifted spectral lines of molecules in distant galaxies can nowadays be measured with extreme precision due to developments in large dish optical telescopes and in radio-astronomy. Via these means tiny shifts in the transition frequencies of spectral lines can be detected, of course after correction for the high redshift of the absorbing clouds and the baryo-centric motion of the telescopes in our galaxy.
Atomic and molecular physicists understand in the finest detail how the quantum level structure of atoms and molecules depends on the two relevant parameters that determine their level structure and their optical and radiofrequency spectrum: the fine structure constant $\alpha$ and the proton-electron mass ratio $\mu$. It is noted that $\mu$ is a mass ratio involving the non-fundamental proton particle; in view of the fact that the mass of the proton originates predominantly in the strong force (the masses of the constituent quarks only contribute for 10%) $\mu$ primarily probes the strength of the nuclear (or strong) force. Theories assuming Grand Unification predict that the coupling constants $\alpha$ and $\mu$ are connected, and that $\mu$ should undergo more rapid changes, if anything varies at all. That makes $\mu$ a good search ground to detect a temporal variation of a fundamental constant per se.

The internal motions of the nuclei in molecules are known to depend on $\mu$. Scaling laws are derived to describe the sensitivity. Internal motions involving quantum tunnelling phenomena are very sensitive, a fact which is well understood from quantum mechanics: tunnelling is exponentially dependent on the mass of the tunnelling particle. Our Amsterdam team has discovered that hindered internal rotation in molecules (which can be considered as a tunnelling motion) can give rise to extremely high sensitivities for $\mu$-variation, in particular for those cases where the energies associated with internal rotation are resonant with energies of overall rotation of the molecule. We have identified the methanol molecule, or CH$_3$OH, the simplest form of alcohol as the most sensitive molecular system for detecting $\mu$-variation [Jan11a]. Some transitions exhibit a sensitivity of a thousand times higher than those for the hydrogen molecule, an often used probe. These spectral lines in methanol fall in the radio-frequency domain, at frequencies between 5 and 200 GHz, and are observable by radio telescopes.

Our project entails detecting the sensitive transitions of methanol in galaxies at high redshift in order to detect a possible variation in the proton-electron mass ratio: $\Delta \mu/\mu$. In a preliminary investigation with the Effelsberg radio telescope in Germany we have demonstrated that observation of the sensitive methanol lines in a gravitationally lensed quasar system at a redshift of $z=0.88$ is possible. This redshift corresponds to a look-back time of 7 billion years toward the origin of the Universe. This paves the way for a more comprehensive radio-astronomical study detecting methanol lines at high precision in a
number of systems at varying redshift to probe constraints or values of $\Delta \mu / \mu$ at improved sensitivity. We have identified a number of other galaxies in front of bright radio quasars that may reveal methanol absorption. In addition to the Effelsberg radio telescope, also the E-VLA radiotelescope in New Mexico (where we have been granted time to observe the $z=0.88$ absorbing galaxy), also the IRAM telescope in southern Spain may be used. We have in addition proposed a plan for the novel radio telescope ALMA in Chile to detect methanol at higher frequencies, made possible by the extreme altitude of ALMA (5 km above sea level); in this plan the ALMA Band-3 receivers can be employed to detect some ten CH$_3$OH lines in a single setting, so an economic use of expensive observation time.

The quantitative target of the present project is to put a constraint on a possible variation of the proton-electron mass ratio at the level of $10^{-8}$. Moreover it is planned to perform such studies in a variety of systems probing different look-back times and different directions in the Universe. These investigations will push the limits on a varying $\mu$ down by an order of magnitude with respect to current state-of-the art. In the unexplored territory below the $10^{-7}$ accuracy level a positive detection of a varying constant may occur. Such a finding would alter our view on the Universe.